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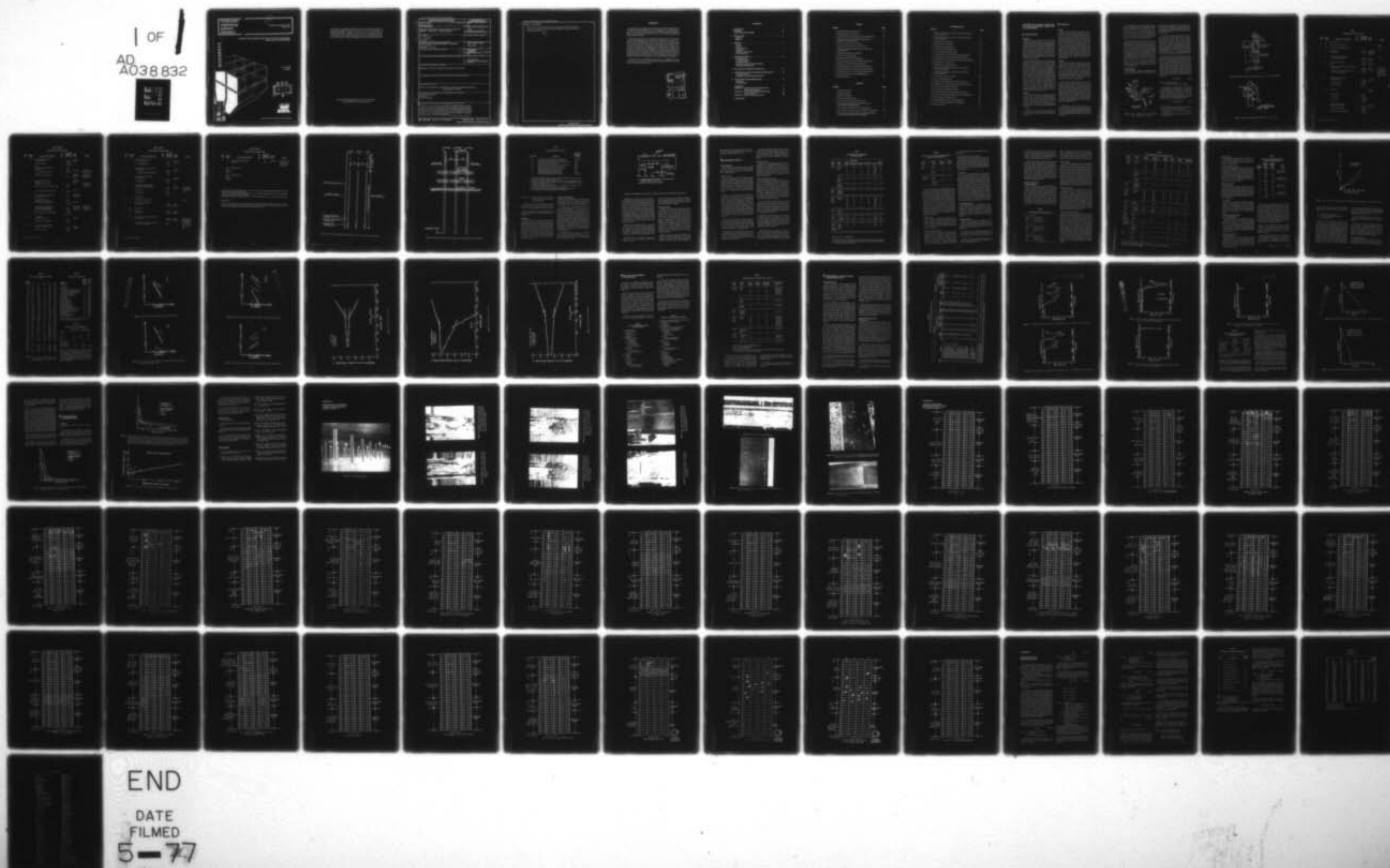

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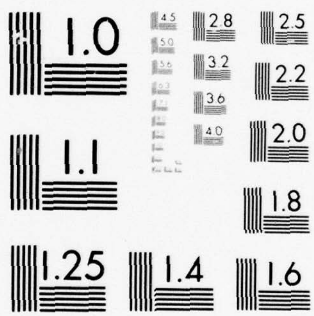

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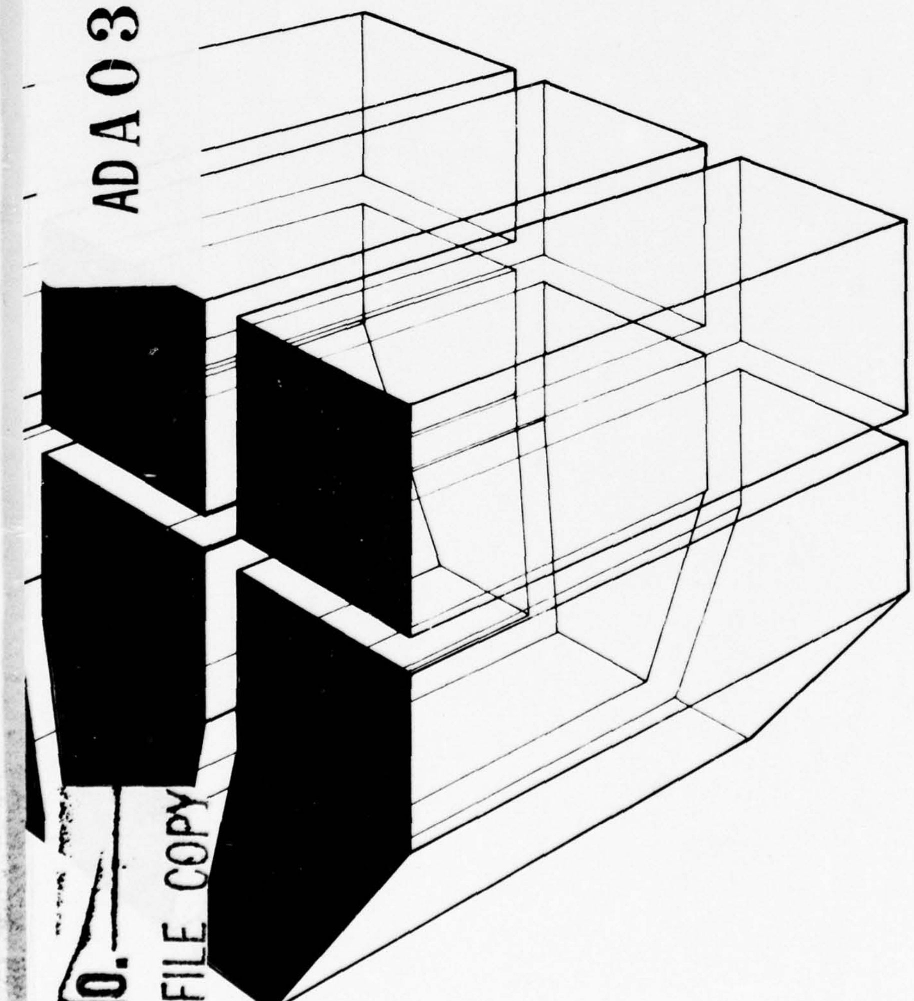
March 1977

COATINGS AND CATHODIC PROTECTION OF PILINGS IN SEAWATER: RESULTS OF 5-YEAR EXPOSURE



by
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A. Kumar

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This report presents the results of the inspection of test pilings extracted after 5 years of exposure to seawater at LaCosta Island, FL. The effectiveness of various coating systems and sacrificial anodes in preventing corrosion of H- and steel pipe pilings in seawater is assessed. Six of the coating systems were found to perform excellently, as was a coating/cathodic protection combination. Sacrificial anodes of zinc and aluminum were also found to effectively reduce corrosion in the immersed zone.

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Block 20 continued.

The study also confirmed that use of the cathodic protection index and polarization behavior is an effective nondestructive testing technique for monitoring corrosion of steel immersed in seawater.

FOREWORD

This investigation was conducted for the Directorate of Civil Works, Office of the Chief of Engineers (OCE) under CWIS 31204 "Corrosion Mitigation in Civil Works Projects." Mr. J. Robertson is the OCE Technical Monitor. The work was performed by the Metallurgy Branch of the Materials and Science Division, U.S. Army Construction Engineering Research Laboratory (CERL).

Appreciation is expressed to Mr. L. Watkins, Mr. M. Dickey, and Mr. J. Lesnick (all of the Coastal Engineering Research Center) and Mr. H. Ardahl (retired from the Corps of Engineers Lower Mississippi Valley Division) for their assistance in the field inspections (1971 through 1974) and personal contacts. Appreciation is also extended to CERL personnel who participated in past inspections: Dr. R. Quattrone, Mr. C. Hahin, Mr. F. Kisters, Mr. J. Aleszka, Mr. G. Schnittgrund, Mr. M. Khobaib, Ms. R. Hannan, and Mr. B. Ching. Other CERL personnel participating in the study were Mr. R. Merritt, who assisted in the structure factor analysis, and Mr. S. Cato, who provided technical assistance. The assistance of Mr. W. Cannaday, CAPT J. Davis, and Mr. R. Cutter of the Corps of Engineers Tampa Bay Area Office, and Mr. A. Pelton of Need-a-Diver in Tampa, FL in the removal and preparation of the pilings for the 5-year inspection is also acknowledged.

Dr. A. Kumar is Chief of the Metallurgy Branch and Dr. G. R. Williamson is Chief of the Materials and Science Division. COL J. E. Hays is Commander and Director of CERL and Dr. L. R. Shaffer is Technical Director.

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COATINGS AND CATHODIC PROTECTION OF PILINGS IN SEAWATER: RESULTS OF 5-YEAR EXPOSURE

1 INTRODUCTION

Background

The Directorate of Civil Works, Office of the Chief of Engineers, has jurisdiction over many structures, such as harbors, bridges, and buildings, which are supported on pilings in coastal areas. Steel pipe and H-pilings have generally been used for foundations in coastal areas; more recently, prestressed concrete pilings have also been used. However, designers of such structures are faced with a problem: quantitative data on the rate of piling corrosion and the performance of coatings and sacrificial anodes on steel pilings under long-term field exposures are not available.

In response to this problem, the U.S. Army Corps of Engineers and the National Bureau of Standards (NBS) initiated a corrosion study in 1967, when 31 sets of piles (three identical piles per set) were installed near Dam Neck, VA. Every 5 years, one row of piles was to be extracted and examined for corrosion damage. To determine the effect of geography and temperature, two more sites (LaCosta Island, FL and Buzzards Bay, MA) were selected by the Coastal Engineering Research Center (CERC), which evaluated the pilings through June 1974, when the inspection responsibility was transferred to the U.S. Army Construction Engineering Research Laboratory (CERL). The installation of 31 sets of three rows of piles at LaCosta Island was completed in January 1971, and annual inspections have been conducted since then. CERL installed the pilings at Buzzards Bay in October 1974 and conducted the first annual inspection in July 1975.[1]

Objective

The objective of this study is to evaluate the effectiveness of various commercially available coatings and sacrificial anodes in preventing corrosion of pilings in seawater. This report summarizes the results of the inspection of test pilings extracted after 5 years of exposure at LaCosta Island, FL, and compares the results to those from the 5-year inspection of the Dam Neck, VA pilings.

[1] A. Kumar and C. Hahin, *First Annual Inspection of Buzzards Bay Pilings*, Technical Report M-172/ADA024381 (U.S. Army Construction Engineering Research Laboratory, [CERL], 1976).

2 APPROACH

Test Site

Figure 1 shows the LaCosta Island test site. The yearly surface water temperature ranges from 55° to 90°F (13° to 32°C), with an approximate mean yearly temperature of 75°F (24°C). The salinity fluctuation due to tidal flushing in LaCosta Island is approximately 30 parts per thousand at low tide to 36 parts per thousand at high tide. Mean tide level at the LaCosta site is 1.3 ft (0.4 m) with a spring tide range of 2.6 ft (0.8 m). Wave action is light, and the bottom material is composed of approximately equal proportions by weight of silica sand and shell. In comparison, the bottom material at the Dam Neck site consists mostly of fine silica sand with a relatively thin layer of clay near the surface. This fine sand is easily carried into suspension by the surf, causing erosion-corrosion* of the pile surfaces.

Test Piles

The test piles included H- and pipe piles made of either American Society for Testing and Materials (ASTM) A 36 or ASTM 690 (mariner steel). The steel H piles are 6 in. × 6 in. × 30 ft (15.2 cm × 15.2 cm × 9.1 m) and weigh 25 lb/ft (37.2 kg/m). Stainless steel rods were welded between the inside flanges of each pile so that electrical contact could be made for electrochemical measurement. Figures 2 and 3 show the detail sections of the H- and pipe piles. Six prestressed concrete piles were also installed.

Some piles were installed without any coating or sacrificial anodes, while others have both coatings and cathodic protection. Most of the protective coating systems included in the LaCosta Island study are the same as those at the Dam Neck site. The systems include organic coatings, metallic coatings, organic over metallic, metal-filled organic, and organic over metal-filled. (See Table 1 for a complete list of the coatings and their sources.) The coatings were applied after the base metal was sandblasted to near "white metal" according to Steel Structures Painting Council (SSPC) Specification SSPC-SP-10-63T.

*Erosion-corrosion is an accelerated attack on the metal due to the movement between the corrosive fluid and the metal surface. The corroding metal forms solid corrosion products which are swept away, revealing fresh metal for further corrosion. Although seashells are softer than steel, seashells (limestone) suspended in seawater will cause erosion-corrosion of steel piling.

The sacrificial anodes for the cathodically protected piles were mounted near the sand zone and consisted of zinc or aluminum. The zinc anodes are 4 X 4 X 36 in. (10.1 X 10.1 X 91.4 cm) and weigh about 150 lb (68.0 kg) when new; the aluminum anodes are 4 X 4 X 38 in. (10.1 X 10.1 X 96.7 cm) and weigh 60 lb (27.2 kg) when new. Two such anodes were installed on each pile to be cathodically protected.

The pilings were jetted into place in three rows parallel to the shoreline (Figures 4 and 5). The rows are designated A, B, and C, with row A being nearest the beach and row C farthest from the beach. Of the 31 sets of three piles, three are bare carbon or mariner steel, two are prestressed concrete, and the remaining are coated steel. Two of the coated steel pile sets are also cathodically protected. The coated piles in row A are completely coated; the coated B piles are entirely coated with the exception of seven 6 X 1 in. (15.2 X 2.5 cm) windows (at 2, 7, 14, 17, 20, 22, and 27 ft [0.6, 2.1, 4.3, 5.2, 6.1, 6.7, and 8.2 m] from the bottom of the pile on the piling surface facing the beach), and the C piles are completely coated, except for the embedded zone.

Annual Inspections

After placement, the pilings were subjected to five annual inspections consisting of visual observations and electrochemical measurements. Visual observations included complete evaluation of coating deterioration in accordance with ASTM Standard Methods for Evaluating Degree of Rusting on Painted Steel Surfaces, D 610-68 (Table 2).

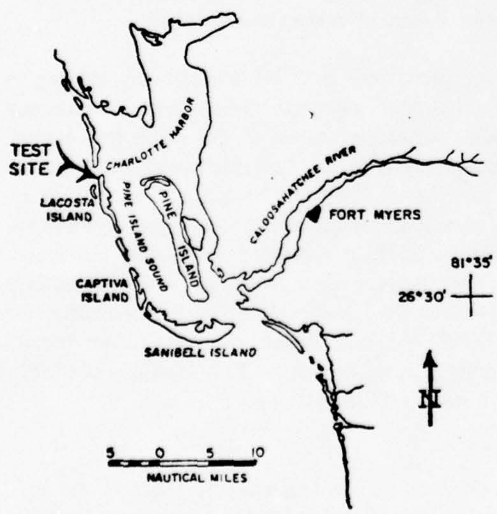

Figure 1. LaCosta Island test site. SI conversion factor: 1 nautical mile = 1.852 km.

Three types of electrical measurements were taken: pile corrosion potential measurements, cathodic protection index measurements, and polarization measurements. Electrical contact with the stainless steel rods in the piles was made using vise clamps connected to the cable wires. The pile potential measurements were made on piles provided with sacrificial anodes to indicate the protection offered by the anodes. A Miller Model M-3-M Multimeter was used to measure the potential with respect to a copper-copper sulphate electrode buried in damp sand and shielded from the sun.

The cathodic protection indices (CPI) were determined for all coated piles except those with sacrificial anodes by forming a galvanic couple between two piles of a set and then measuring the potential with zero applied current. The current was then increased to lower the initial potential measured by 0.150 V for the metallic coated piles and 0.85 V for the other coated piles. The current was constantly adjusted to keep the lowered value of the potential constant during a 5-minute run. The initial and final values of the current and potential were then used to calculate the CPI value using Eq 1.

$$CPI = \Delta V/\Delta I \qquad \text{[Eq 1]}$$

where ΔV = change in voltage
ΔI = current required to shift the voltage.

The corrosion rate measurements were conducted by Schwerdtfeger and McDorman's[2] "polarization break" method, which uses breaks in the anodic and cathodic polarization curves to identify the corrosion rate via a calculated corrosion current, I_c. I_c can be calculated from the following relationship, which was derived by Pearson[3] and confirmed by Holler:[4]

$$I_c = (I_p)(I_q)/(I_p + I_q) \qquad \text{[Eq 2]}$$

[2]W. J. Schwerdtfeger and O. N. McDorman, *Journal of the Electrochemical Society*, Vol 99 (1952), p 407.

[3]J. M. Pearson, *Transactions of the Electrochemical Society*, Vol 81 (1942), p 485.

[4]H. D. Holler, *Journal of the Electrochemical Society*, Vol 97 (1950), p 277.

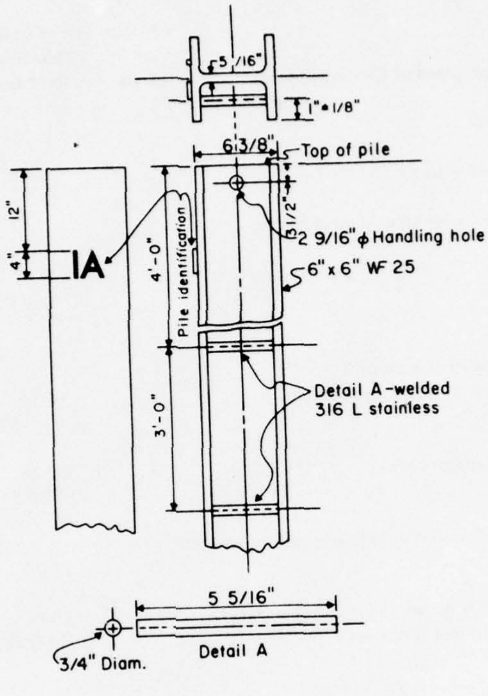

Figure 2. Dimensions of H-piles. SI conversion factors: 1 in. = 2.54 cm; 1 ft = 0.3048 m.

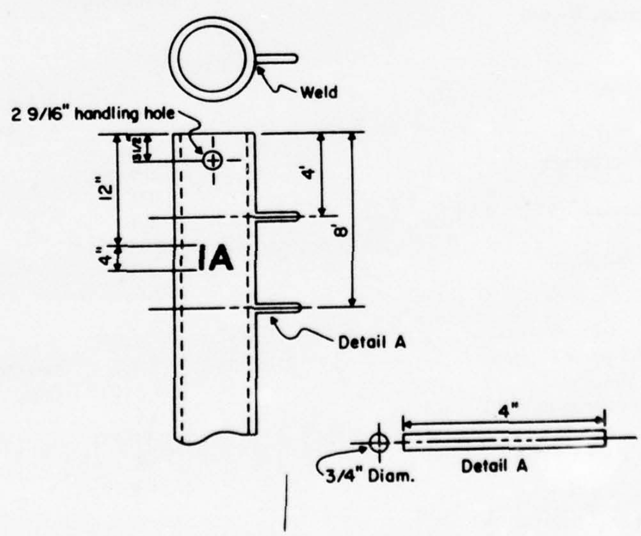

Figure 3. Dimensions of pipe piles. SI conversion factor: 1 in. = 2.54 cm.

Table 1

Test Pile Details, LaCosta Island Test Site

System No.	Type of Piling*	Description of Coating System	No. of Coats	Dry Coating Thickness, mils** (mm)	Coating Source	Remarks
1	H	Bare carbon steel	–	–	–	–
2	H	Bare carbon steel with zinc anodes	–	–	–	2 anodes
3	H	Bare carbon steel with aluminum anodes	–	–	–	2 anodes
4	H	Coal-tar epoxy Formula C-200	2	16-20 (0.41-0.51)	United States Steel (U.S.S.) Chemicals	–
5	H	Coal-tar epoxy with zinc anodes Formula C-200, polyamide-cured	2	16-20 (0.41-0.51)	U.S.S. Chemicals	2 anodes
6	H	Coal-tar epoxy, amine-cured Tarset	2	16-20 (0.41-0.51)	U.S.S. Chemicals	–
7	H	Coal-tar epoxy, aluminum-oxide-armored at mud line Formula C-200	2	16-20 (0.41-0.51)	U.S.S. Chemicals	Third coat + garnet to be applied between 11 and 17 ft (3.3 and 5.2 m) from bottom of pile
		Formula C-200 + aluminum oxide (No. 30 grit) broadcast into wet final coat	1	10-11 (0.25-0.28)		
8	H	Aluminum-pigmented epoxy-tar Carbomastic #3	1	8-9 (0.20-0.23)	Carboline Co.	–
		Carbomastic #12-14	1	7-8 (0.18-0.20)		
		Carbomastic #5-140	1	4 (0.10)		
9	H	Coal-tar epoxy			U.S.S. Chemicals	
		U.S.S. epoxy primer	1	3 (0.08)		
		Tarset Standard	1	8-10 (0.20-0.25)		
		Tarset Standard	1	8-10 (0.20-0.25)		
10	H	Epoxy over inorganic ceramic Plas-Chem Zinc-ite G primer	1	3-4 (0.8-0.10)	Plas-Chem Corp.	
		Plas-Chem's Ceram-ite #101	1	5-6 (0.13-0.15)		
		Plas-Chem's 2140 Z high build epoxy	1	7-8 (0.18-0.20)		

See footnotes at end of table, p 13.

Table 1 (Cont'd)

Test Pile Details, LaCosta Island Test Site

System No.	Type of Piling*	Description of Coating System	No. of Coats	Dry Coating Thickness, mils** (mm)	Coating Source	Remarks
11	H	Epoxy over inorganic zinc primer				
		Zincor #11 primer	1	1-1.5 (0.03-0.04)	Plas-Chem Corp.	
		Chem-Pon 2310X Red	1	8-9 (0.20-0.23)		
12	H	Saran				
		Washcoat primer, Mil-P-15328B (Formula 117)	1	0.4 (0.01)		
		Formula 113/54; Mil-L-18389	7	6-7 (0.15-0.18)	Navy Stock	Alternate coat white and orange
13	H	Aluminum, flame-sprayed (wire)	1	6 (0.15)	Metalweld, Metco, or other	Steel wire flash bonding coat, 1 mil (0.03 mm)
14	H	Aluminum, flame-sprayed (wire) vinyl topcoat			Metalweld, Metco, or other	
		Flame-sprayed aluminum (wire)	1	6 (0.15)		Steel wire flash bonding coat 1 mil (0.03 mm)
		Washcoat primer, Formula 117, MIL-P-15328B	1	0.4 (0.01)		
		Alum. vinyl, Metcoscal-AV (Alum, Vinyl)	2	2 (0.05)	Metco, Inc.	
15	H	Zinc, flame-sprayed, with saran topcoat Steel wire flash bond coat	1	1 (0.03)	Metco Metal weld or other	
		Flame-sprayed zinc ([illegible]e)	1	6 (0.15)		
		Saran, Formula 113/54, alternate white and orange; finish coat, white	7	6-7 (0.15-0.18)	Navy stock	
16	H	Zinc, flame-sprayed, with Navy vinyl topcoat, Flame-sprayed zinc (wire)	1	6 (0.15)	Metco Metal weld or other	Steel wire flash bonding coat, 1 mil (0.03 mm)
		Washcoat primer, MIL-P-15328B	1	0.4 (0.01)	Navy Stock	
		Vinyl red-lead, Formula 119, MIL-P-15929	5	4-5 (0.10-0.13)		
17	H	Phenolic Mastic				
		Phenoline 300 (orange)	1	8 (0.20)	Carboline Co.	
		Phenoline 300 (gray) finish coat	1	8 (0.20)		
18	H	Coal-tar epoxy over organic zinc-rich				
		U.S.S. zinc-rich epoxy No. 110	1	3 (0.08)	U.S.S. Chemicals	
		Coal-tar epoxy, C-200	2	12 (0.30)		

See footnotes at end of table, p 13.

Table 1 (Cont'd)

Test Pile Details, LaCosta Island Test Site

System No.	Type of Piling*	Description of Coating System	No. of Coats	Dry Coating Thickness, mils** (mm)	Coating Source	Remarks
19	H	Vinyl over inorganic zinc-rich				
		U.S.S. zinc-rich No. 220	1	3 (0.08)	U.S.S. Chemicals	
		U.S.S. high-build vinyl	1	7 (0.18)		
20	H	Epoxy-polyamide over inorganic zinc-rich				
		Carbozinc #11	1	3 (0.08)	Carboline Co.	
		High-build epoxy polyamide 190 HB	2	12 (0.30)		
21	H	Epoxy-tar over inorganic zinc-rich				
		Carbozinc #11	1	3 (0.08)	Carboline Co.	
		Carbomastic #14	1	8 (0.20)		
22	H	Vinyl Mastic over inorganic zinc-rich				
		Dimetcote #3+D3 Curing Solution	1	3 (0.08)	Amercoat Corp.	Curing solution to be removed by fresh water wash
		#54 Tie Coat	1	1 (0.03)		
		Vinylmastic #87	1	10 (0.25)		
23	H	Bare mariner steel	–	–	–	–
24	H	Bare mariner steel with zinc anodes	–	–	–	2 anodes
25	H	Coal-tar epoxy on mariner steel				
		Formula C-200	2	16-20 (0.41-0.51)	U.S.S. Chemicals	–
26	Pipe	Bare carbon steel	–	–	–	–
27	Pipe	Coal-tar epoxy Formula C-200	2	16-20 (0.41-0.51)	U.S.S. Chemicals	
28	Pipe	Coal-tar epoxy, garnet-armored at mud line				
		Formula C-200	2	16-20 (0.41-0.51)	U.S.S. Chemicals	Third coat and aluminum oxide to be applied between 11 and 17 ft (3.3 and 5.2 m) from bottom of pile
		Formula C-200 + aluminum oxide (#30 grit) broadcast into wet final coat	1	10 (0.25)		

See footnotes at end of table, p 13.

Table 1 (Cont'd)

Test Pile Details, LaCosta Island Test Site

System No.	Type of Piling*	Description of Coating System	No. of Coats	Dry Coating Thickness, mils** (mm)	Coating Source	Remarks
29	H	Polyester glassflake, Carboglas 1601, spray grade	2	40 (1.02)	Carboline Co.	Blast material to provide 3-4 mil (0.08-0.10 mm) surface profile
30	Concrete 10 in. (25.4 cm) square	Prestressed Concrete				
31	Concrete 10 in. (25.4 cm) octagon	Prestressed Concrete				

* Steel H-piles are 30-ft (9.1 m) lengths of 6 in. X 6 in. (15.2 cm X 15.2 cm) wide flange (25 lb/ft [37.2 kg/m]) mild carbon steel. Systems 23, 24, and 25 are mariner steel H piles.
Systems 26, 27, and 28 are pipe piles, mild carbon steel, 6 in. (15.2 cm) diameter, schedule 40, 0.280 in. (0.7 mm) wall thickness. Prestressed concrete piles are as stated in this column.

** Film thickness tolerance per coat may be plus or minus 15 percent of given thickness per coat, except where a range is given.

GENERAL NOTES:

All surfaces were blast-cleaned to near-white metal prior to coating. Systems 28 and 29 were supplied in the near-white condition. Specimens were numbered A, B, or C, which corresponds to their position (A faces the shore, B in the center, and C faces the Gulf), and have a numeric prefix which designates in what manner they were coated.

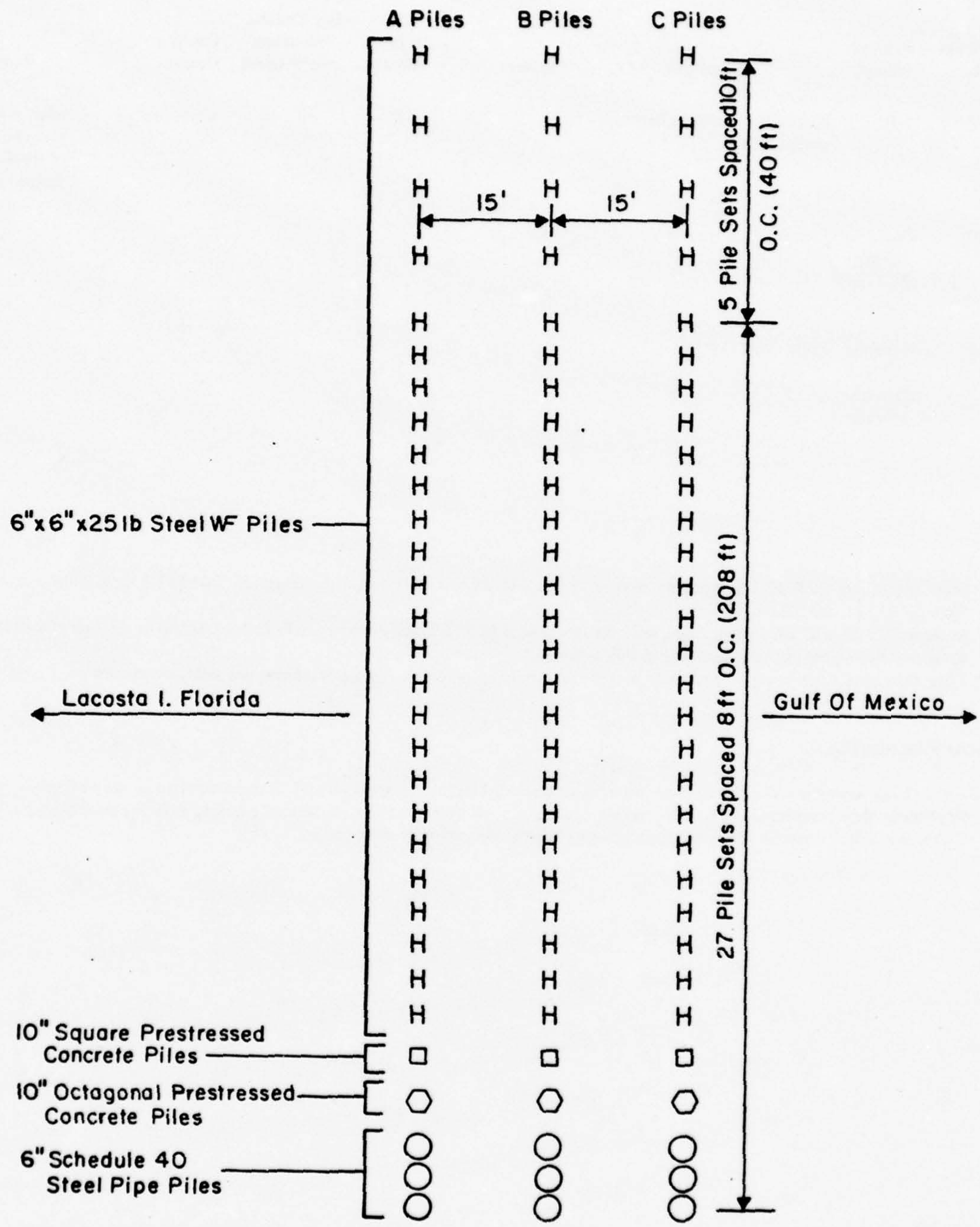

Figure 4. Plan of LaCosta Island test piles. SI conversion factors: 1 in. = 2.54 cm; 1 ft = 0.3048 m.

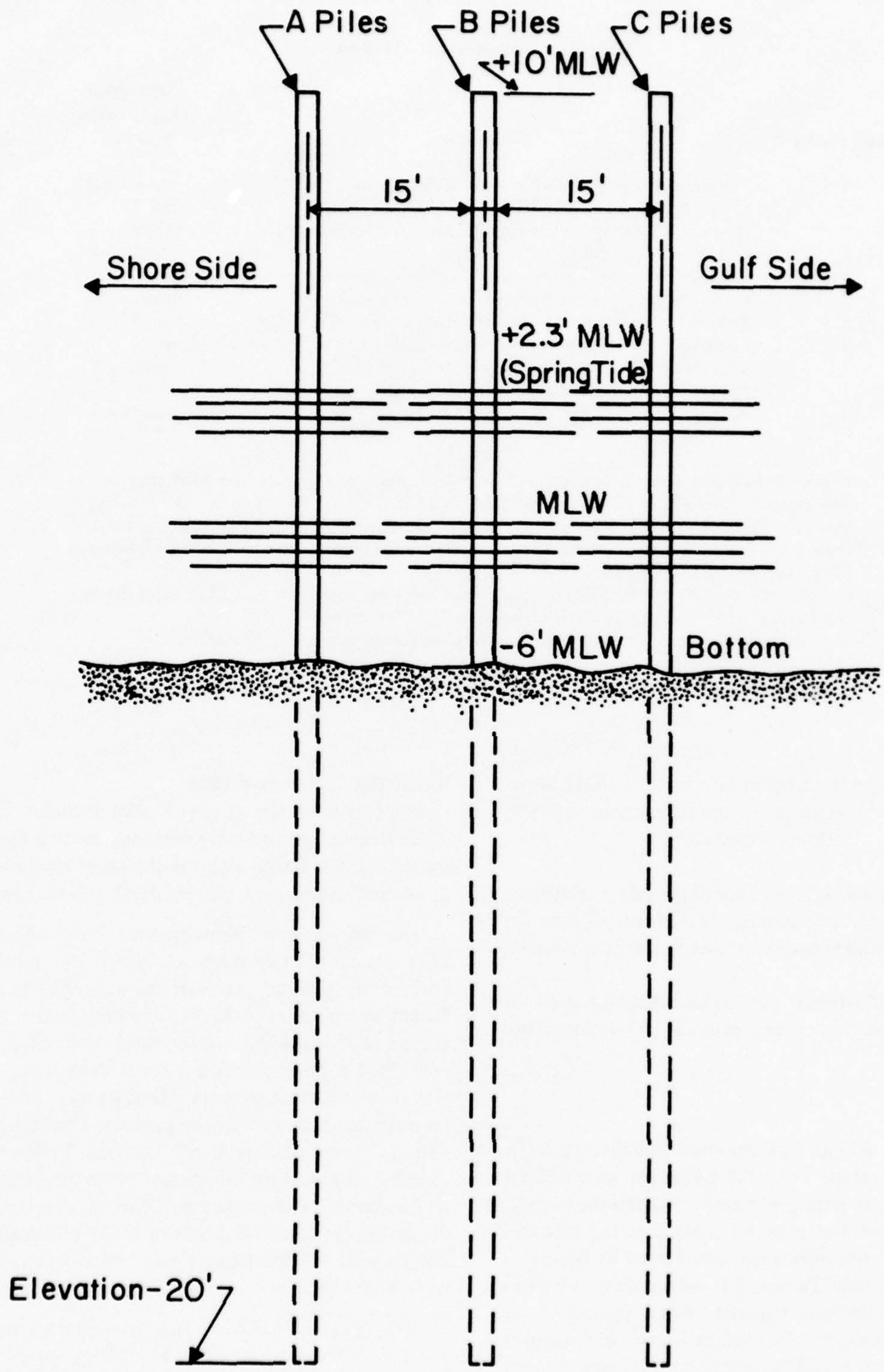

Figure 5. Elevation of pile set for LaCosta Island test site. SI conversion factor: 1 ft = 0.3048 m.

Table 2

Scale and Description of Rust Grades*

Rust Grades**	Description	SSPC-ASTM Photographic Standard
10	No rusting or less than 0.01 percent of surface rusted	unnecessary
9	Minute rusting, less than 0.03 percent of surface rusted	No. 9
8***	Few isolated rust spots, less than 0.1 percent of surface rusted	No. 8
7	Less than 0.3 percent of surface rusted	none
6†	Extensive rust spots but less than 1 percent of surface rusted	No. 6
5	Rusting to the extent of 3 percent of surface rusted	none
4††	Rusting to the extent of 10 percent of surface rusted	No. 4
3†††	Approximately one-sixth of the surface rusted	none
2	Approximately one-third of the surface rusted	none
1	Approximately one-half of the surface rusted	none
0+	Approximately 100 percent of the surface rusted	unnecessary

* Reprinted with permission of American Society for Testing and Materials from *Evaluating Degree of Rusting on Painted Steel Structures*, ASTM D 610-68.

** Similar to European Scale of Degree of Rusting for Anti-Corrosive Paints (1961) (black and white).

*** Corresponds to SSPC Initial Surface Conditions E (0 to 0.1 percent) and BISRA (British Iron and Steel Research Association) 0.1 percent.

† Corresponds to SSPC Initial Surface Conditions F (0.1 to 1 percent) and BISRA 1.0 percent.

†† Corresponds to SSPC Initial Surface Condition G (1 to 10 percent).

††† Rust grades below 4 are of no practical importance in grading performance of paints.

\+ Corresponds to SSPC Initial Surface Condition H (50 to 100 percent).

where I_p and I_q = the tangent intersections of the linear portions of the anodic and cathodic curves, respectively.

These polarization curves are obtained by increasing the current from zero in equal increments of time (in this case 0.1-ampere increments at 5-minute intervals).

Figure 6 illustrates the circuit diagram used in making the polarization and cathodic protection index measurements.

Pile Removal

The row C pilings were removed in February 1976 by hooking a crane onto the pull-holes provided on the pilings. Water jetting was used to loosen the bottom material around the piles to prevent piling damage. After removal, the piles were transported by barges to a storage area near Tampa, FL, where they were unloaded onto concrete supports. Wood separators on the supports protected the coatings from being damaged by contact with a hard surface. The piles were spaced to allow easy access and room to turn the piles for inspection of all surfaces.

Inspection of Removed Piles

Inspection of the removed piles included coating evaluation before and after cleaning, coating thickness measurements, flange and web thickness measurements of all sandblasted piles, and pit depth measurements.

The pilings were photographed both before and after cleaning (Appendix A). Since the piles were covered by pelican guano in the atmospheric zone,* fouled by marine organisms in the immersed zone, and coated with attached oyster shells and sand in the embedded zone, more than a conventional water wash was required to clean them. Hand-scraping and water-blasting removed most of the guano and marine fouling without severe damage to the coatings. Following the cleaning, the coating thicknesses were measured with an Elcometer, where possible. Charts were constructed displaying the corrosion behavior of the pilings (Appendix B), and the coated piles were rated in accordance with ASTM D 610-68.

*For discussion purposes, each 30-ft (9.1 m) length of piling is divided into four zones: atmospheric zone (0 to 6 ft [0 to 1.8 m]), immersed zone (6 to 17 ft [1.8 to 5.2 m]), sand-swept zone (17 to 21 ft [5.2 to 6.4 m]), and embedded zone (21 to 30 ft [6.4 to 9.1 m]).

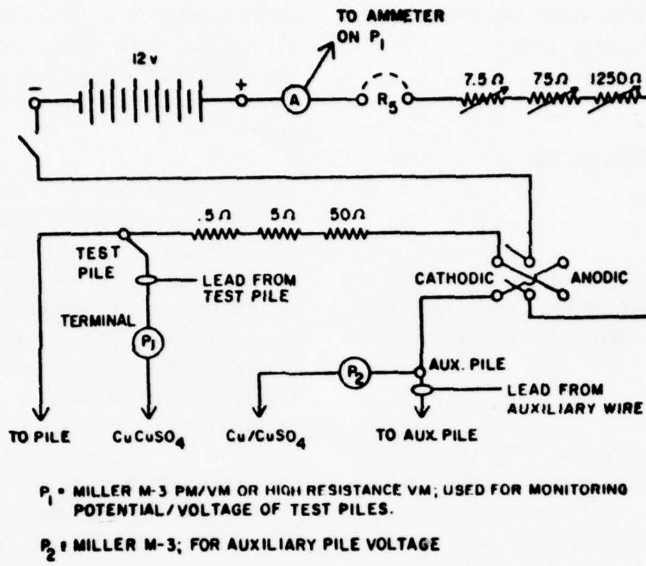

Figure 6. *Circuit diagram for measurement of cathodic protection index and polarization measurements.*

Sandblasting was required to permit measurement of metal thickness and determination of pit depth. As an alternative to the extensive sandblasting required to remove the attached oyster shells and sand from the buried zone, a conventional water-blaster capable of adding an abrasive to the water stream* was used on some of the more stubborn fouling. Results indicated that this unit could be used for both the cleaning and coating-removal steps. It was cleaner, faster, and less polluting than sandblasting, and its capability of adding a rust inhibitor would prevent the piles from further rusting during the examination period. This would ensure that the surface examined would still be in the as-blasted condition.

Following the sandblasting operation, a pit depth profile was made for each of the piles containing pits, and flange and web thicknesses were determined along the lengths of the piles. The piles with the coatings removed were photographed to provide a visual record of pit shape, size, and distribution. The average corrosion rate was determined from the average web and flange thickness measurements. The pit depth data were also used in establishing surface factors for the pits according to type and distribution of damage.

Pile Structure Factor

The piles under examination were subjected only to stresses induced by current flow. Since there was no actual loading of the piles (as would be experienced in-service), there was no visible evidence of structural deterioration caused by diminishment of cross section due to corrosion or erosion-corrosion. However, since changes in pile dimensions could be measured, determining an estimated pile structure factor based on known changes in dimension and the condition of the pile surface was possible. Appendix C presents the derivation of a general expression that considers stresses involved in loading the piles based on the assumption that the upper part of the pile is the point of attachment.

Basically, the pile structure factor (PSF) is the product of a quantitative measurement of the pile section based on corrosion measurements and a qualitative assessment of the pile surface. The calculation of a

*The unit used was the Aqua-Blaster manufactured by Partek Corp., Houston, TX and available from Boos Industrial Equipment, Tampa, FL.

PSF permits ranking of piles according to their structural performance and placing them into one of four categories—excellent, good, fair, or poor.

3 DISCUSSION OF RESULTS

Visual Observations

Table 3 presents the surface factors and the ASTM D 610-68 evaluation results for the coated steel piles. Table 4 gives the surface factors for the cathodically protected and bare piles.

Organic Coatings

Most of the damage to the coal-tar epoxy coatings occurred in the immersed zone due to attack by marine organisms (especially barnacles). The coal-tar coatings held up very well in the sand-swept zone, where marine organisms could not attach themselves to the pile due to the abrasiveness of the sand-sea water slurry. This abrasion was not great enough to cause significant damage to the coatings, and no erosion-corrosion was noted.

System 9, a coal-tar epoxy over an epoxy primer, gave better protection than coal-tar epoxy alone, as expected; this was demonstrated by the undamaged surface observed after coating removal. System 7, a coal-tar epoxy with an alumina armor in the sand-swept zone, also showed no significant surface damage on coating removal. Coal-tar performed better on mariner steel than on carbon steel. The surface factors show that the polyamide-cured Formula C-200 (system 4) provided better protection than the Tarset (system 6) in the immersed zone, while the harder Tarset gave better abrasion resistance than the C-200 in the sand-swept zone.

The saran (polyvinylidene chloride) coating (system 12) gave excellent protection in the atmospheric and sand-swept zones, but was completely removed in the immersed (marine-fouled) zone. Upon coating removal, the pile surface was irregular and had many continuous shallow pits in the immersed zone.

The phenolic mastic coating (system 17) was somewhat damaged in the atmospheric and immersed zones, but held up excellently in the sand-swept zone. Upon coating removal, only slight damage was noted on the flanges in the atmospheric zone.

The polyester glassflake coating (system 29) gave the best results of any coating in the entire study, with an excellent visual rating in all three evaluated zones and an excellent surface factor. The marine fouling was removed very easily, and no significant damage was present.

Metal-Filled Coatings

Only system 8, an aluminum-pigmented epoxy-tar, was classified as metal-filled. This coating held up excellently in the atmospheric and sand-swept zones, but suffered severe rusting, staining, and pitting in the immersed zone. Upon coating removal, the surface throughout the immersed zone was found to contain a large number of deep pits, as evidenced by the surface factor rating of 3.

Organic Over Metal-Filled Systems

Seven coatings with electrically insulating top coats fell into this classification. System 10, a high-build epoxy over a zinc-rich primer, gave excellent protection in all three zones; there was no indication of significant corrosion damage. System 20, another high-build epoxy over zinc-rich primer, gave excellent protection in the atmospheric and immersed zones, but was almost completely removed in the sand-swept zone. After coating removal, the pile surface showed some pitting in the sand-swept zone, with isolated pits on the faces and edges of the flanges.

The coal-tar epoxy over zinc-rich primer (system 18) exhibited excellent protection in the atmospheric and sand-swept zones, but performed poorly in the immersed zone. However, on coating removal, the metal surface was essentially undamaged—an indication that the primer was effective although the visual rating of the coating indicated otherwise.*

High-build vinyl (system 19) and epoxy over zinc-rich primer (system 11) indicated fair to excellent protection in all but the immersed zone, where removal of the coating again revealed that the metal surface was not severely damaged. The epoxy system showed somewhat greater damage in the immersed zone, with a roughened surface and a few pits.

*This often happens in visual ratings of two-or-more-coat systems over primers or metallized coatings. Breakdown of the surface coating allows corrosion products to appear on the surface, thus giving an apparently lower visual rating. On coating removal, the metal surface is found to be essentially undamaged, in direct contradiction to the visual rating.

Table 3

Visual Evaluation* of Coated Steel Piles, LaCosta Island Test Site

System Class	System Type	System Number	Zone Evaluated: Atmospheric	Immersed	Sand-Swept	Average	Surface Factor**
Organic	Coal-tar epoxy	9	10	8	10	9.33	10
		7	6	8	10	8.00	10
		25	9	4	8	7.00	8
		6	7	3	10	6.87	5
		4	9	4	7	6.33	7
	Saran	12	10	0	10	6.67	6
	Phenolic mastic	17	7	8	10	8.33	9+
	Polyester glassflake	29	10	10	10	10	10
Metal-filled	Aluminum-pigmented epoxy-tar	8	9	3	10	7.33	3
Organic over metal-filled	Zinc-rich primer	18	9	6	10	8.33	10
		10	10	9	10	9.67	10
		20	10	9	2	7.00	8
		19	7	1	10	6.00	9
		11	6	1	9	5.33	8
		21	9	1	3	4.67	4
		22	7	2	3	4.00	6
Metallic	Flame-sprayed, Al	13	7	8	5	6.67	10
Organic over metallic	Vinyl (Al)	14	8	7	3	6.00	10
	(Zn)	16	10	8	3	7.00	9
	Saran (Zn)	15	5	1	3	3.00	8
Organic coating with cathodic protection	Coal-tar epoxy with zinc anodes	5	10	9	10	9.67	10
		25	9	4	8	7.00	9

*Visual Ratings Based on ASTM D 610-68.

**Surface factor based on the condition of the pile after blast cleaning, according to type and distribution of damage. A rating of 10 indicates surface undamaged and a rating of 1 indicates severe surface damage that could result in structural failure.

Table 4

Surface Factors for Uncoated and Cathodically Protected Steel Piles, LaCosta Island Test Site

System Class	System Type	System Number	Surface Factor
Bare piles	Carbon steel	1 26	2 2
	Mariner steel	23	4
Cathodically protected	Zinc anodes	2 24	4 7
	Aluminum anodes	3	3

The last two systems in this classification gave poor performances in the immersed and sand-swept zones. System 21 (epoxy-tar over zinc-rich primer) performed very well in the atmospheric zone, resulting in good visual ratings during annual inspections; however, removal of the pile revealed extensive damage to the coating and pile surface. The immersed and sand-swept zones were severely pitted on all faces and flanges. The vinyl mastic over zinc-rich primer (system 22) provided only fair protection in the atmospheric zone, while the immersed and sand-swept zones received considerable damage. On coating removal, these two zones showed some surface damage in the form of a series of shallow interconnected pits on the faces and isolated pits on the edges of the flanges.

Metallic Coatings

Only system 13, a flame-sprayed aluminum, came under the metallic classification. Visually, this coating displayed significant rusting in all three zones, but on coating removal the surface was excellent, indicating that the sacrificial protection offered by the coating was still in operation.

Organic Over Metallic Systems

Vinyl was used as a coating for both flame-sprayed aluminum and zinc. Visually, the zinc (system 16) appeared to be providing better protection, but the aluminum-coated pile (system 14) showed a better surface on coating removal. Saran over flame-sprayed zinc (system 15) appeared to be giving very little protection, but on removal, the surface of the pile had only been slightly damaged in the immersed and sand-swept zones.

Organic Coating With Cathodic Protection

Coal-tar epoxy with zinc anodes was used on both carbon (system 5) and mariner (system 25) steels. The system provided better protection to the carbon steel than the mariner steel, especially in the immersed zone. The carbon steel surface was virtually undamaged, while the mariner steel had some slight roughening in the immersed zone.

Uncoated Piles

The bare piles (both unprotected and protected) were rated to obtain a surace factor to be used in the structural analysis (Table 4). As the table indicates, only the mariner steel with zinc anodes provided better than a poor surface. The other bare piles were corroded severely in the atmospheric zone, with less corrosion in the immersed zone. Corrosion was minimal and no evidence of pitting was present on the cathodically protected piles. Because the anodes protect against corrosion only in the immersed section of the piles (the salt water acts as a medium for electron exchange), the air-exposed portion (atmospheric zone) is free to corrode. This is the zone where significant corrosion occurred. The bare mariner steel provided somewhat better protection than the bare carbon steel, which was severely pitted and contained holes in the web.

Pit Depth Measurements

The pit depth data were used *qualitatively* in establishing the surface factors listed in Tables 3 and 4. This information is important in considering the structural degradation of pilings subjected to corrosion, but would be more useful if a procedure for determining pit density as a function of pit surface area and depth existed.

Pile Structure Factor

Table 5 lists pile performances based on the PSF according to the magnitude of the importancy factor, k_2, which reflects the sensitivity of the PSF to surface condition. The magnification factor, k_1, is held constant at 0.1.*

As Table 5a shows, the PSF is less sensitive to the large variations in surface condition (structural surface factor) when the importancy factor is assigned a value

*Appendix C describes the complete derivation of the structure factor equation, and details the definition of the importancy and magnification factors.

of 0.5. With an importancy factor of 1.0 (Table 5b), the PSF varies linearly with variations in the surface condition. With yet another increase in the importancy factor (k_2 equals 2.0, Table 5c), the PSF becomes very sensitive to small changes in surface condition.

The piles were ranked according to their calculated PSF and grouped into categories based on structure factor and surface condition. After considering the relationship between visual observations and PSF, the linear model (Table 5b) was chosen as the basis for evaluating the total effectiveness provided by each system. In all, seven piles were rated excellent, six good, five fair, and eight poor. Appendix C presents the complete results of the structure factor analysis, including the actual pile rankings and weighting, magnification, and importancy factors.

Correlation of Visual and Structural Properties

Table 6 illustrates the correlation between the visual and structural characteristics of the steel pilings and gives a total view of the protection offered by each system. It indicates the weakest coated area and average coating evaluations based on ASTM D 610-68, the surface rating based on magnitude of surface factor, the structural rating (from Table 5b), and the overall effectiveness of the protection. The weakest coated area evaluation was included to point out that coatings can be rated as good overall but perform poorly in a particular area of importance. It also illustrates that the surface coatings may be rated poor even though the piles are structurally sound due to sufficient primer or metallizing. The surface and coating characteristics were compared with the structural character of the system to determine the system's overall effectiveness.

Table 5

Pile Performance Based on Structure Factor

a. $k_1 = 0.1, k_2 = 0.5$		
	Excellent	– 29, 18, 10, 14, 5, 9, 13
	Good	– 24, 7, 16, 25, 17
	Fair	– 20, 15, 4, 22, 19, 6
	Poor	– 21, 8, 11, 12, 2, 3, 23, 1
b. $k_1 = 0.1, k_2 = 1.0$		
	Excellent	– 29, 18, 10, 14, 5, 9, 13
	Good	– 7, 16, 25, 17, 20, 15
	Fair	– 24, 4, 22, 19, 6
	Poor	– 21, 8, 11, 12, 2, 3, 23, 1
c. $k_1 = 0.1, k_2 = 2.0$		
	Excellent	– 29, 18, 20, 10, 15
	Good	– 7, 16, 14, 25, 17, 5, 9
	Fair	– 13, 4, 22, 24, 6, 19
	Poor	– 21, 8, 11, 12, 2, 23, 3, 1

Organic Coatings

In the organic coating class, the polyester glassflake (system 29) and C-200 coal-tar epoxy over epoxy primer (system 9) were found to be providing excellent protection. Coal-tar epoxy with aluminum oxide armor (system 7), coal-tar epoxy over mariner steel (system 25), and phenolic mastic (system 17) showed good protection. Coal-tar epoxy C-200 (system 4) gave fair protection, while Tarset coal-tar (system 6) and saran (system 12) provided poor protection. For nearly all coatings in the organic class, the effectiveness of protection was primarily affected by coating (and hence steel) degradation in the immersed zone, where marine fouling damaged the coating and promoted corrosion.

Metal-Filled Coatings

The one system in the metal-filled class—the aluminum-pigmented epoxy-tar (system 8)—was rated as poor. This was a three-coat system in which two coats of epoxy-tar electrically insulated the outer coat containing the aluminum pigment from the metal. This system's mechanism for sacrificial protection depends on electron exchange between the pigment and the steel, which can come about only through a very slow diffusion mechanism; thus, the aluminum pigment cannot provide sacrificial protection. The coating was perforated by barnacles, which are suspected of causing the severe pitting in the immersed zone.

Organic Over Metal-Filled Systems

Overall, this class provided very good protection although visual analysis indicated only fair performance. This system's effectiveness depends on the capability of the metal-filled primers to provide sacrificial protection; the cover coat is a diffusion barrier. Epoxy over inorganic ceramic and zinc-rich primer (system 10) was rated excellent in all areas, while coal-tar epoxy over an organic zinc-rich (conductive) coating (system 18) provided excellent overall protection. High-build vinyl (system 20) and high-build epoxy (system 19) on inorganic zinc-rich primers were rated as good; epoxy (system 11) and vinyl (system 22) over zinc-rich primers were rated as fair; and epoxy-tar over an inorganic zinc-rich primer was rated poor. Again, most of the coating degradation leading to corrosion was in the immersed zone due to marine fouling.

Table 6

Correlation of Visual and Structural Characteristics*

System Class	System Type	System Number	Weakest Coated Area**	Coating Average†	Surface Factor	Structure Factor	Effectiveness of Protection
Organic coatings	Coal-tar epoxy	9	G-I	E	E	E	E
		7	P-A	G	E	G	G
		25	P-I	G	E	G	G
		6	P-I	F	P	F	P
		4	P-I	F	F	F	F
	Saran	12	P-I	F	P	P	P
	Phenolic mastic	17	G-A	G	E	G	G
	Polyester glassflake	29	E	E	E	E	E
Metal-filled	Aluminum-pigmented epoxy tar	8	P-I	G	P	P	P
Organic over metal-filled	Zinc-rich primers	18	P-I	G	E	E	E
		10	E	E	E	E	E
		20	P-S	G	G	F	G
		19	P-I	F	E	F	G
		11	P-I	P	G	P	F
		21	P-I, S	P	P	P	P
		22	P-I, S	P	G	P	F
Metallic	Flame-sprayed Al	13	P-S	F	E	E	E
Organic over metallic	Vinyl (Al)	14	P-S	F	E	E	E
	(Zn)	16	P-S	F	E	G	G
	Saran (Zn)	15	P-I, S	P	G	F	F
Organic coating with cathodic protection	Coal-tar epoxy	5	E	E	E	E	E
	with zinc anodes	25	P-I	G	E	G	G
Cathodically protected	Zinc anodes	2	–	–	P	P	P
		24	–	–	G	F	F
	Aluminum anodes	3	–	–	P	P	P
Bare piles	Carbon steel	1	–	–	P	P	P
		26	–	–	P	–	–
	Mariner steel	23	–	–	P	P	P

*Ratings: E = Excellent, G = Good, F = Fair, P = Poor.
**Area of coating suffering the most damage – A = Atmospheric, I = Immersed, S = Sand-swept.
†Rating based on performance in all zones.

Metallic Coatings

Flame-sprayed aluminum (system 13), which was the only metallic coating without a cover coat, was found to provide excellent protection in spite of its only fair visual performance.

Organic Over Metallic Systems

Overall, this classification is rated very good. In the vinyl system, the aluminum flame-sprayed provided better protection than the zinc flame-sprayed system. The saran over zinc flame-sprayed system was only fair. These performances suggest that the sacrificial protection offered by the flame-sprayed metals is still operative after 5 years immersion, with aluminum providing better protection than zinc.

Organic Coatings with Cathodic Protection

The very effective protection offered by the coal-tar epoxy zinc anode combinations (systems 5 and 25) indicates that an organic coating coupled with cathodic protection provides an effective means of protecting the exposed portion of the piling, as well as cathodically protecting the immersed section should any break in the coating occur.

Uncoated Piles

The unprotected steel piles failed due to severe rusting in the atmospheric zone. When cathodically protected, the air-exposed part of the steel corroded severely, since the sacrificial anodes are only operative in the salt water. The mariner steel performed well enough in the atmospheric zone to be classified as fair overall.

Electrochemical Measurements

Potential Measurements

The potentials of the protected piles (Table 7) were measured with respect to a copper-copper sulphate half-cell. The results of the 1972 and 1976 inspections show that no significant changes in potentials have occurred, although a slight trend toward higher cathodic potentials can be observed. These results indicate that the sacrificial anodes are providing protection in the immersed zone.

Cathodic Protection Index (CPI) Measurements

The CPI indicates the current required to cathodically protect the bare area in the immersed zone by determining the amount of current required to shift the potential of the pile in the cathodic direction by 150mV, or attain -0.85 V with respect to copper-copper sulphate electrode.

Table 7

Potentials of Protected Piles With Respect to Copper-Copper Sulphate Half-Cell

Pile Number and Row	Inspection Results 1972 Voltage	Inspection Results 1976 Voltage	Nature of Coating
2 A	1.080	1.11	Bare carbon steel with zinc anodes
B	1.808	1.05	
C	1.080	1.10	
3 A	0.990	1.09	Bare carbon steel with aluminum anodes
B	0.990	1.05	
C	0.995	1.05	
5 A	1.080	1.09	Coal-tar epoxy with zinc anodes
B	1.100	1.10	
C	1.090	1.09	
24 A	1.075	1.10	Bare mariner steel with zinc anodes
B	1.080	1.10	
C	1.080	1.10	

Recent laboratory investigations of vinyl and coal-tar epoxy coatings and bare steel immersed in tap and salt water at CERL have demonstrated the direct correlation between change in current and change in bare steel area (Figure 7). Since CPI is inversely proportional to the change in current (by Eq 1), a direct correlation exists between CPI and bare steel exposed to an aqueous medium. A decrease in CPI is indicative of a larger area of bare steel exposed to water (larger change in current required); a decrease in CPI is therefore an indication of coating deterioration.

Figure 7 also demonstrates the need for higher currents for cathodic protection in salt water, which is more corrosive than tap or fresh water; thus, the magnitude of the CPI also depends on the test or service environment.

Table 8 shows the CPI for the 1972 through 1976 pile measurements. The 5 years of data show CPI vs time of exposure as a straight line on log-log coordinates, indicating that the CPI follows a relation of the type:

$$CPI = Kt^{m} + Co \qquad \text{[Eq 3]}$$

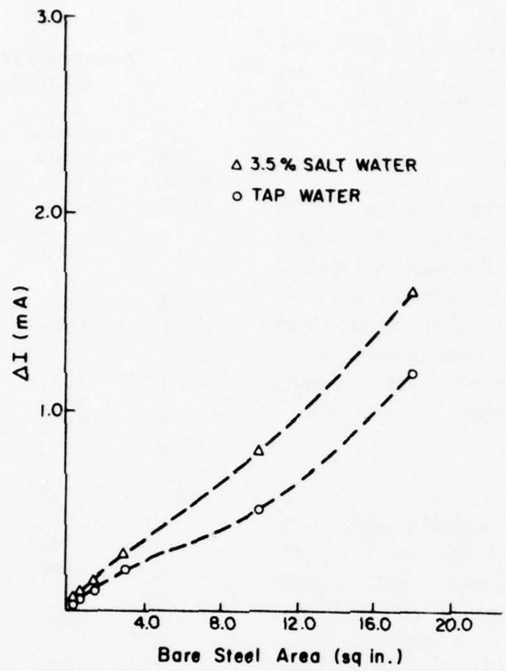

Figure 7. ΔI as a function of bare steel area in tap and salt water. SI conversion factor: 1 sq in. = 6.4156 cm^2.

where m ~ -0.65, with values ranging from +1.688 to -1.890 (indicates rapidity of decay of coating effectiveness)

K = ordinate intercept at log t = 1
Co = constant at t (initial CPI at immersion)
t = time of exposure.

Plotting the cathodic protection indices vs. time durations on log-log plots (Figures 8 through 11) permits prediction of the deterioration of the coatings over a long period of time. Deterioration of the coatings generally resulted in a drop in CPI, as demonstrated by a negative slope averaging approximately -0.65 for all coatings (Figures 8 through 10). However, some coatings, such as flame-sprayed metallics, have a completely flat slope or a slightly positive one, indicating formation of protective corrosion products, such as aluminum oxide or zinc oxide, in the porous flame-sprayed metal. All other systems show negative logarithmic behavior, with decay of index m depending on the coating and mil thickness. Slopes for piles with and without windows are the same for each particular coating, but the absolute values of the CPIs of piles with windows are always lower.

Table 9 summarizes the values of the exponent m, which measures the rapidity of decay of coating effectiveness.

Comparison of Table 6 and Figures 8 through 11 shows a very strong correlation between the rank of the effectiveness of protection and CPI for all independent generic systems. Only in the category of organic over metal-filled coatings is the correlation weakened, possibly because of the difference in conductivity of the various metal-filled undercoats.

Polarization Measurements

The corrosion rate or rate of metal loss can be determined from the average corrosion current density: the higher the corrosion current density, the higher the

Table 8

Cathodic Protection Indices of the Pilings* (V/A)

Pile Number and Row	1972	1973	1974	1975	1976
4A	8.95	3.61	1.6	1.14	1.72
4B	2.38	1.72	1.1	0.71	1.63
6A	7.00	2.21	1.3	0.76	1.54
6B	1.45	0.930	0.68	0.59	1.89
7A	13.0	9.10	7.2	5.67	5.06
7B	3.02	2.46	2.0	1.98	2.43
8A	21.7	3.76	1.7	0.92	1.72
8B	2.48	1.48	1.1	0.59	4.59
9A	19.7	15.5	1.1	8.42	7.23
9B	1.97	1.94	1.6	1.46	2.11
10A	4.17	3.26	2.4	0.23	0.37
10B	4.02	4.55	3.8	4.17	3.26
11A	0.303	0.139	0.12	0.11	1.37
11B	0.257	0.137	0.11	0.11	1.30
12A	0.271	0.162	0.12	0.11	1.40
12B	0.510	0.228	0.15	0.13	1.36
13A	3.85	5.17	5.4	4.69	4.59
13B	3.66	5.12	5.7	6.00	5.00
14A	6.45	3.23	.2	13.64	16.30
14B	4.20	5.36	5.6	7.50	5.25
15A	0.518	0.794	.81	1.13	2.34
15B	0.426	0.593	.75	1.07	2.54
16A	0.728	0.893	1.5	2.11	3.49
16B	0.987	0.938	.13	1.97	4.69
17A	11.3	4.11	2.9	1.47	2.04
17B	2.27	1.88	1.3	1.03	1.74
18A	34.2	17.4	10	6.30	0.46
18B	2.47	2.2	1.6	1.30	1.91
19A	2.18	0.327	0.21	0.19	1.50
19B	0.975	0.282	0.17	0.16	1.32
20A	70.8	46.9	21	23.08	16.85
20B	2.63	2.73	3.7	4.05	5.67
21A	53.6	39.0	24	48.39	16.00
21B	2.05	1.41	0.65	0.35	1.35
22A	1.98	2.13	0.32	0.18	1.34
22B	2.79	2.03	0.50	0.27	1.33
25A	15.4	5.00	1.7	1.07	18.91
25B	2.52	1.53	0.78	0.62	1.74
26A					
26B					
27A	7.87	5.30	4.0	3.7	4.25
27B	2.09	2.34	1.9	1.89	2.25
28A		7.75	3.7	2.94	3.26
28B		2.85	1.9	1.94	2.21
29A	17.9	12.5	10	7.92	7.69
29B	2.44	2.38	2	2.14	2.88

*CPI = $\Delta V/\Delta I$

where ΔI = the current required to shift the voltage to -0.85 V with respect to a copper-copper sulphate half-cell

ΔV = the change in voltage.

Table 9

Deterioration of Coating Systems

Generic Classification	Coating System Code Number	Rapidity of Decay, m*
Coal-tar epoxy	4	−1.800
Coal-tar epoxy	6	−1.716
Coal-tar epoxy, aluminum-oxide-armored	7	−0.571
Coal-tar epoxy, aluminum-pigmented	8	−1.890
Coal-tar epoxy, aluminum-pigmented	9	−0.543
Coal-tar epoxy, organic zinc	18	−1.195
Coal-tar epoxy, inorganic zinc	21	−0.637
Coal-tar epoxy	25	−1.890
Coal-tar epoxy	27	−0.577
Epoxy, inorganic zinc	10	−0.485
Epoxy, inorganic zinc	20	−0.834
Epoxy, inorganic zinc	11	−0.227
Vinyl, inorganic zinc	19	−0.655
Vinyl mastic, inorganic zinc	22	−1.031
Flame-sprayed aluminum	13	+0.145
Flame-sprayed aluminum, vinyl topcoat	14	+1.688
Flame-sprayed zinc, saran topcoat	15	+0.543
Flame-sprayed zinc, Navy vinyl	16	+0.782
Phenolic mastic	17	−1.476
Saran, MIL-L-18389 primer	12	−0.818
Polyester glassflake	29	−0.576

*Negative m indicates decay of the coating rating, whereas positive m indicates rating improvement.

Table 10

Polarization Data for LaCosta Island Pilings

Variable	Bare Carbon Steel 1	Coating Systems 7	Coating Systems 28
I_p, mA	500	150	380
I_q, mA	440	150	378
$(I_p)(I_q)(I_p+I_q)$	234	75	189
Average corrosion current density, mA/sq ft (mA/m^2)	2.92 (0.27)	0.93 (0.09)	2.30 (0.49)

metal loss or the corrosion rate. Table 10 summarizes the corrosion current densities per square foot, based on Schwerdtfeger's equation (Eq 2), for systems 1, 7, and 28. Determination of I_p and I_q was accomplished by extending the tangents of linear portions of the curves and determining their intersection, as shown in Figures 12 through 14.

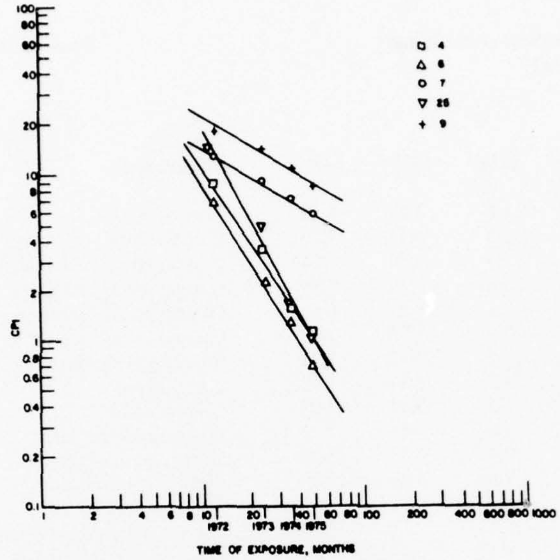

Figure 8. CPI as a function of time of exposure for organic coating systems.

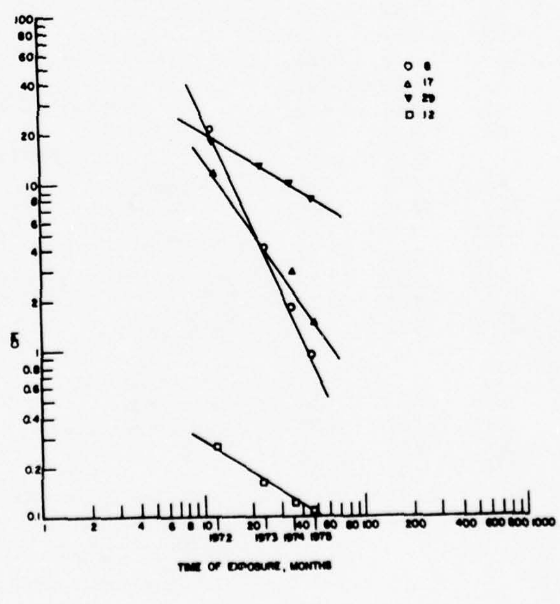

Figure 9. CPI as a function of time of exposure for miscellaneous organic coatings and metal-filled organic coating systems.

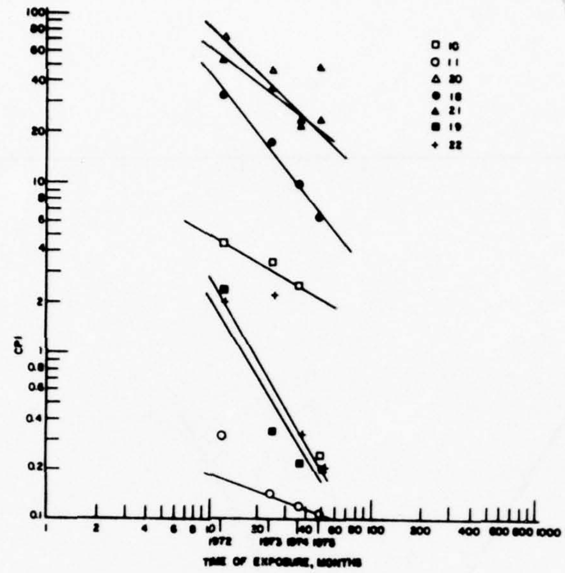

Figure 10. CPI as a function of time of exposure for organic over metal-filled coating systems.

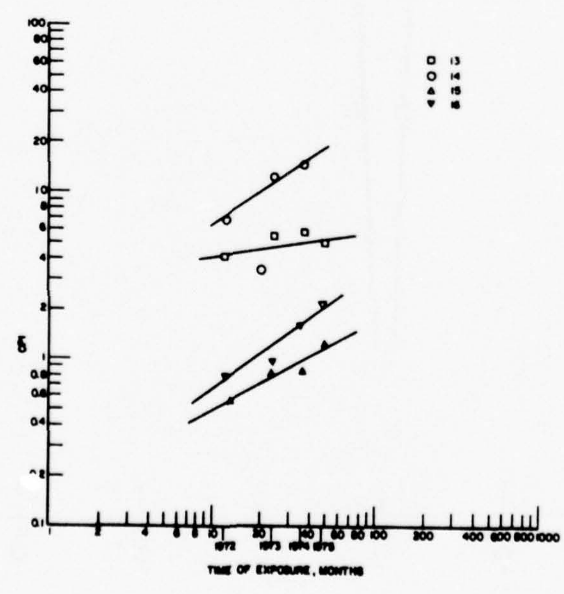

Figure 11. CPI as a function of time of exposure for metallic and organic over metallic systems.

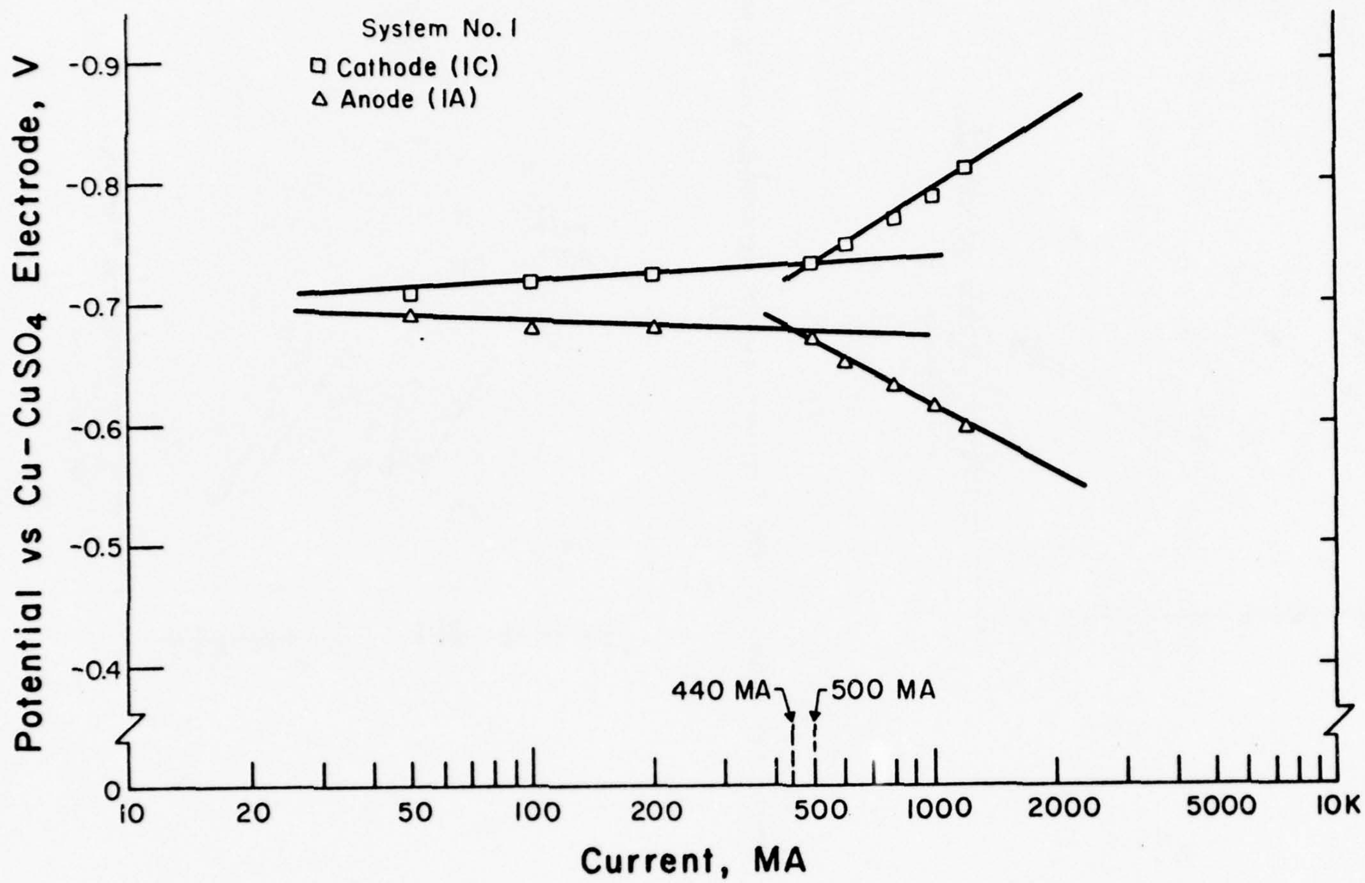

Figure 12. Polarization curves for system 1.

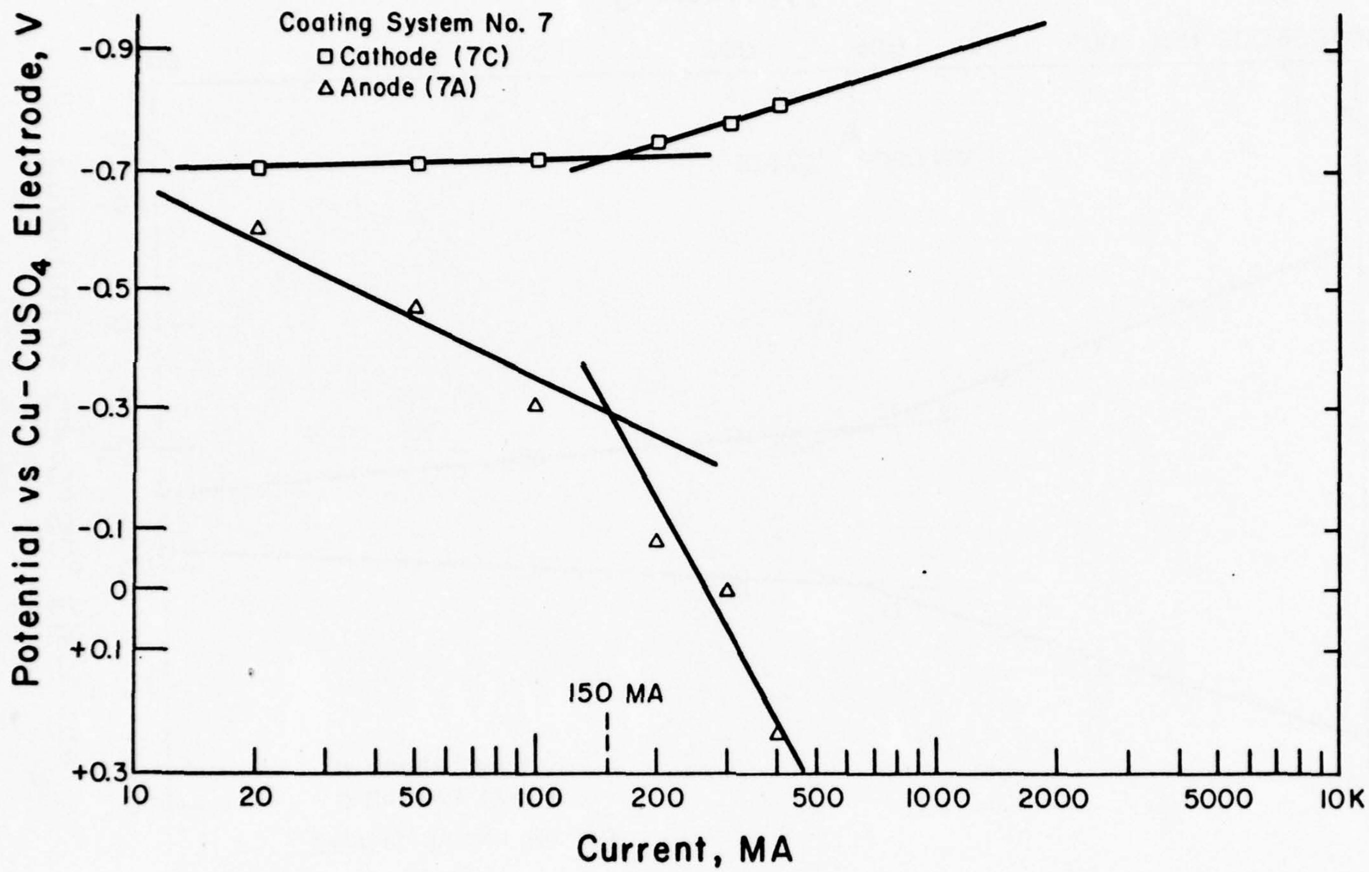

Figure 13. Polarization curves for system 7.

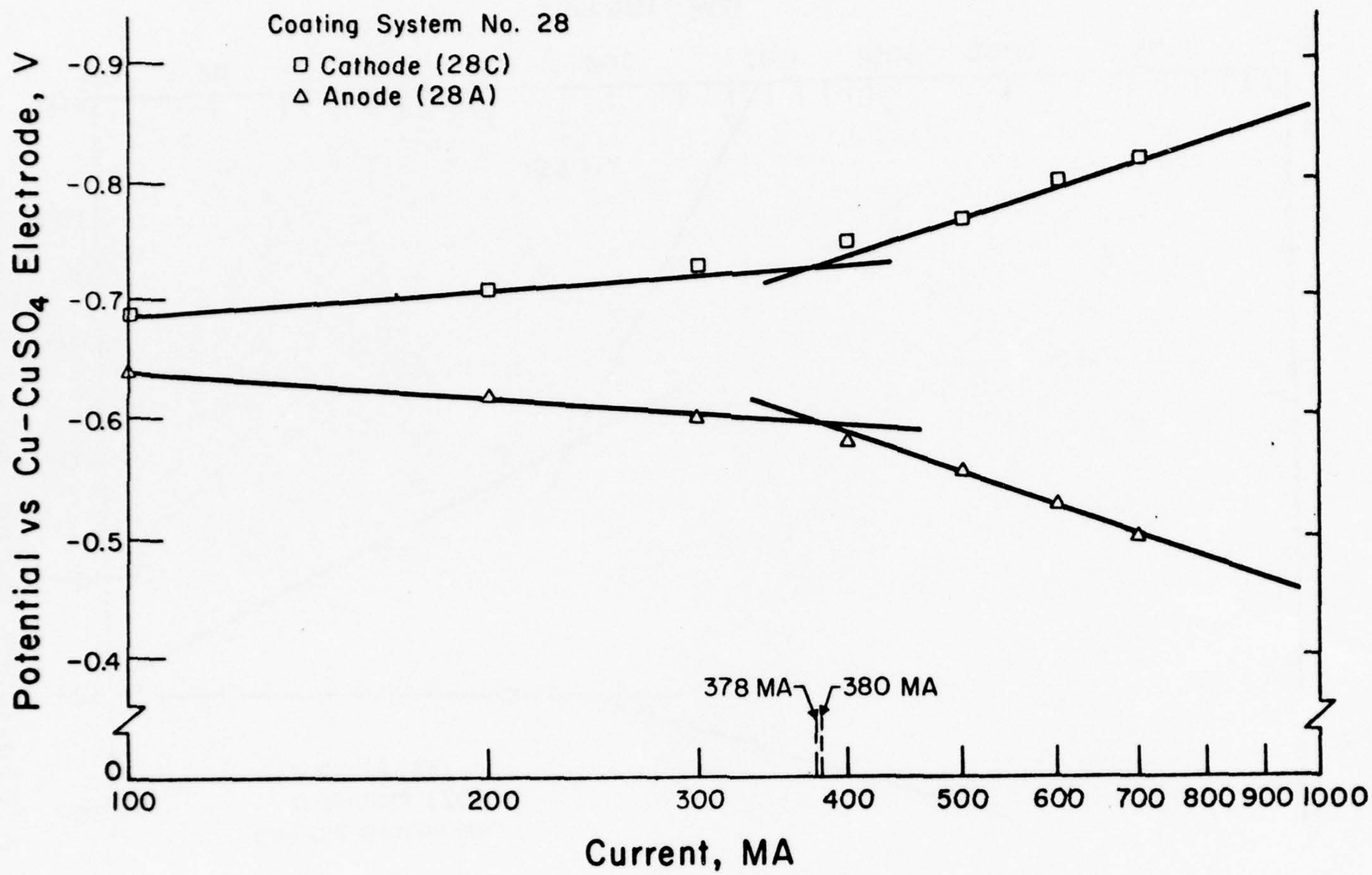

Figure 14. Polarization curves for system 28.

4 COST AND EFFECTIVENESS OF PROTECTION

The total cost of preparing and applying a protective coating to a new steel structure depends on many factors (Table 11). This cost, however, is only one of the variables to consider in selecting a coating system (Table 12).

Most of the items shown in Tables 11 and 12 are themselves composed of many factors, depending on the actual application. Consequently, estimating and comparing all these factors for the numerous coatings considered in this study would be a time-consuming task. However, if all factors except the cost of the coating itself, the number of coats, and the effectiveness of protection provided are assumed constant for all the coatings, the cost per square foot of each coating system at the recommended thickness can be estimated and compared with the protection provided (Table 13).

In general, the coatings providing the best protection are more expensive, although some of the more expensive coatings are also providing only fair to good protection.

Of the systems providing excellent protection, system 9 (coal-tar epoxy over an epoxy primer) was the least costly (24¢/sq ft [$2.58/m^2$]), followed closely by a high-build epoxy over an organic zinc-rich primer (system 18) at 28¢/sq ft ($3.01 m^2$). Others providing excellent protection were system 10 (high-build epoxy over inorganic zinc-rich primer) at 35¢/sq ft ($3.77/m^2$), polyester glassflake (system 29) at 41¢/sq ft ($4.41/m^2$), flame-sprayed aluminum (system 13) at 50¢/sq ft ($5.38/m^2$), and vinyl-sealed flame-sprayed aluminum (system 14) at 58¢/sq ft ($6.24/m^2$).

Good protection was afforded by coating systems ranging between 16¢ and 58¢/sq ft ($1.72 and $6.24/m^2$), while fair coating systems were on the order of 16¢ to 46¢/sq ft ($1.72 and $4.95/m^2$), and poor coating systems ranged from 15¢ to 21¢/sq ft ($1.61 to $2.26/m^2$).

Table 11
Factors Affecting Total Cost of Coating New Steel Structures

- I. Surface Preparation
  - A. Blasting, degreasing
  - B. Inspection
  - C. Touch-up blasting
  - D. Inspection
- II. Application of Coating
  - A. Number of coats
    - 1. Millage per coat
    - 2. Total millage
  - B. Type of application
    - 1. Type of equipment
    - 2. Associated material losses
  - C. Inspection
  - D. Touch-up
    - 1. Surface preparation
    - 2. Special touch-up materials
  - E. Inspection
- III. Materials
  - A. Coating
  - B. Thinner
  - C. Solvent (cleanup)
  - D. Rags, etc.
  - E. Touch-up
  - F. Shipping
    - 1. Non-government-furnished
    - 2. Government-furnished

Table 12
Variables to Consider in Selecting Coating System

- I. Total cost of preparing and coating (Factors from Table 11)
- II. Durability with respect to application
  - A. Protection
  - B. Appearance
- III. Ease of Application
  - A. Number of coats (Total Millage per Coat)
  - B. Special surface or coating preparation
  - C. Special application environment
    - 1. Humidity
    - 2. Temperature
    - 3. Need for ventilation
  - D. Touch-up
    - 1. Need for special preparation
    - 2. Capability to be touched-up
- IV. Curing
  - A. Environment
    - 1. Humidity
    - 2. Temperature
  - B. Time
    - 1. Need to cure between coats
    - 2. Capability to cure
- V. Safety
  - A. Flammability
  - B. Toxicity
  - C. Ventilation
  - D. Special clothing
  - E. Air-fed respirators
  - F. Solubility in application environment (immersion service)
  - G. Reaction with environment
    - 1. Chemical
    - 2. Physical

Table 13

Relationship Between Cost and Effectiveness of Protection

System Class	System Type	System Number	Total No. of Coats	Effectiveness of Protection	Coating Cost/Sq Ft (/m²)*
Organic coatings	Coal-tar epoxy	9	3	E	24¢ ($2.58)
		7	3	G	16¢** ($1.72)
		25	2	G	16¢ ($1.72)
		6	2	P	16¢ ($1.72)
		4	2	F	16¢ ($1.72)
	Saran	2	8	P	†
	Phenolic mastic	17	2	G	24¢ ($2.58)
	Polyester glassflake	29	2	E	41¢ ($4.41)
Metal-filled	Aluminum-pigmented epoxy-tar	8	3	P	21¢ ($2.26)
Organic over metal-filled	Zinc-rich primers	18	3	E	28¢ ($3.01)
		10	3	E	35¢ ($3.77)
		20	3	G	25¢ ($2.69)
		19	2	G	25¢ ($2.69)
		11	3	F	31¢ ($3.34)
		21	2	P	15¢ ($1.61)
		22	3	F	46¢ ($4.95)
Metallic	Flame-sprayed aluminum	13	2	E	50¢ ($5.38)
Organic over metallic	Vinyl††				
	(aluminum)	14	4	E	58¢ ($6.24)
	(zinc)	16	7	G	58¢ ($6.24)
	Saran (zinc)	15	9	F	40¢ ($4.31)+

* Based only on cost of coating per applied thickness.
** Does not include aluminum oxide grit.
† Saran coating is no longer made.
†† The vinyl in this case refers to a sealer which is mostly absorbed by the porous metallic coating.
\+ Cost does not include saran, which is no longer made.

Since the coating cost has been estimated to be 15 to 25 percent of the total cost of applying a coating to a new structure, the cost of the coating is secondary to the effectiveness of protection. After 5 years, six of the individual coating systems have provided excellent protection at a reasonable cost. The flame-sprayed aluminum is more expensive than the organic coatings, but has been found by other investigators[5] to be providing excellent protection after more than 18 years of immersion service.

[5] C. F. Schrieber, F. N. Longo, and G. J. Duiman, *Proceedings of the Offshore Technological Conference, Report No. 159* (1974).

5 COMPARISON OF LACOSTA ISLAND AND DAM NECK SITES

Environmental Effects

Table 14 compares the data gathered after the removal of pilings from the LaCosta Island and Dam Neck sites. In addition to the rank, average visual rating (ASTM D 610-68), and corrosion rate listed for Dam Neck,[6] this table also provides the normalized structure factor and coating costs for LaCosta Island. The information from this table, along with the physical characteristics of the two sites (Table 15), indicates the difference in corrosion behavior that can be associated with the contrast in environment.

Since the mechanism of corrosion depends on the corrosion environment, temperature, salinity, water (wave) velocity, and bottom composition can affect the extent and form of corrosion. It is well known that corrosion reactions (kinetics) increase with temperature and that the velocity and composition of the corroding slurry affect the extent of erosion-corrosion. Marine (biological) fouling, which depends on water velocity, temperature, biological slime film, type and texture of surface, gravity, light, exfoliating nature, and surface free energy,[7] can also affect coating performance.

Table 15 indicates the physical differences in the LaCosta Island and Dam Neck sites. At LaCosta Island, the mean yearly temperature is 23°F (10°C) higher, the salinity 6.2 ppt higher, and the wave action less severe than at Dam Neck. At Dam Neck the wave action is quite severe, since the pilings are exposed directly to the Atlantic Ocean and the wave action associated with coastal weather. The strong surf action and crosscurrents associated with the Dam Neck site cause suspension of large volumes of sand and debris, which impinge on the piles, thus increasing susceptibility to erosion-corrosion damage. Local eddy currents caused by the pilings also increase the water velocity in the vicinity of the pilings. The bottom elevation of the Dam Neck site is continually changing due to local sand action and movement of sand associated with winter storms, hurricanes, and long summer swells.[8] In contrast, the LaCosta Island site is well protected from violent wave action. The bottom material at LaCosta Island consists of coarse sand and shell, while that of Dam Neck is primarily fine sand over a thin layer of clay. These contrasts in physical characteristics suggest that the LaCosta Island site would be more conducive to damage by marine organisms and higher average corrosion rates (associated with increase in temperature and salinity), while Dam Neck would be affected more by erosion-corrosion and damage to the atmospheric-splash zone. Successful coatings at LaCosta Island would be those more resistant to attack by marine organisms, while the durability and abrasion resistance of the coatings at Dam Neck would be more important factors.

Table 14 indicates the importance of the location and physical environment on the protective behavior of any system. Coal-tar epoxy over zinc-rich primer, vinyl-sealed, flame-sprayed aluminum, and polyester glassflake performed extremely well at both locations; similarly, the coal-tar epoxies and saran did fairly and poorly, respectively, at both sites.

Comparison of Corrosion Rate Profiles and CPI

Figures 15 through 19 give the corrosion rate profiles for pilings of bare carbon steel, bare mariner steel, cathodically protected bare carbon steel, coal-tar epoxy with cathodic protection, and coal-tar epoxy over an organic zinc-rich primer exposed at LaCosta Island. The corrosion profiles are very similar for all systems in the embedded zone, since all pilings were bare in this zone. The average corrosion rate for the embedded zone was found to be 1.1 mil/year (0.03 mm/year), which is comparable to the value of 1.4 mil/year (0.04 mm/year) found by Hunter and Horton[9] to be the corrosion rate of steel embedded in sand.

A slight increase in the corrosion rate in the sand-swept zone was noticed for the bare pilings with and without cathodic protection. This indicates that damage due to erosion-corrosion is minimal. On coated piles, the rate of corrosion in the sand-swept zone was found to be very low, with the suspended sand and shell acting to clean the surface without appearing to physically damage the coating.

The corrosion profile of the bare mariner steel is very similar to that of the bare carbon steel in both the

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[6] J. R. Lesnick, *Condition of Test Piles After 5 Years of Exposure at Dam Neck, VA*, Interim Report (Coastal Engineering Research Center, 1976).

[7] J. R. Saroyan, et al., *Industrial Engineering Chemical, Proceedings of the Research Division*, 9-2 (1970), p 123.

[8] E. Escalante, et al., *Protection of Steel Piles in a Natural Seawater Environment–Part II*, NBSIR 76-1104 (National Bureau of Standards, 1976).

[9] A. D. Hunter and C. H. Horton, *Underwater Engineering* (November 15, 1960).

Table 14

Summary of Results for LaCosta Island and Dam Neck Sites

		LaCosta Island								Dam Neck ***				
				Corrosion Rate, mil/yr*								Corrosion Rate, mil/yr		
System No.	Description	Rank	Average Visual Rating	Average	Atmospheric Zone (1-6 ft [0.3-1.8m])	Immersed Zone (7-17 ft [2.1-5.2m])	Normalized Structure Factor	Coating Cost,** ¢/Sq ft ($/m²)	Rank	Average Visual Rating	Average	Atmospheric Zone (1-15 ft [0.3-4.6 m])	Immersed Zone (14-20 [4.3-6.1 m])
29	Polyester glassflake	1	10	<0.0	<0.0	<0.1	100.00	41 (4.41)	5	9.3	<0.1	<0.1	<0.1
18	Coal-tar epoxy (C-200)/organic zinc-rich	2	8.33	0.3	0.3	0.3	99.25	28 (3.01)	11	9.1	0.19	0.24	0.15
10	Epoxy/inorganic ceramic	3	9.67	0.81	0.7	0.9	98.96	35 (3.77)	–	–	–	–	–
14	Vinyl/aluminum flame-spray	4	6.00	<0.1	<0.1	<0.1	98.57	50 (5.38)	2	7.3	0.16	0.03	0.32
5	Coal-tar epoxy (C-200)/zinc anodes	5	9.67	0.82	0.1	1.4	98.48	24+A (2.58)	–	–	–	–	–
9	Coal-tar epoxy (Tarset, 3 coats)	6	9.33	1.58	1.4	1.7	98.35	24 (2.58)	–	–	–	–	–
13	Aluminum flame-sprayed	7	6.67	1.41	1.6	1.3	98.23	50 (5.38)	9	7.4	0.03	0	0.17
7	Coal-tar epoxy with alumina armor	8	8.00	0.7	0.7	0.7	97.82	16+ (1.72)	16	8.3	0.55	2.7	0.07
16	Vinyl/zinc flame-spray	9	7.00	1.16	1.0	1.4	97.72	58 (6.24)	18	4.9	1.4	2.3	3.2
25	Coal-tar epoxy (C-200) on mariner steel	10	7.00	0.47	0.3	0.55	97.68	16+M (1.72)	15	7.7	0.53	1.6	0.44
17	Phenolic mastic	11	8.33	1.14	1.4	1.0	97.61	24 (2.58)	8	9.0	0.14	0.21	0.11
20	Epoxy polyamide/inorganic zinc-rich	12	7.00	<0.1	<0.1	<0.1	97.50	25 (2.69)	3	8.3	0.05	0	0.22
15	Saran/zinc flame-spray	13	3.00	1.48	0.3	2.1	97.28	40+PVC (4.31)	6	8.4	0.10	0.29	0.14
24	Bare mariner steel/zinc anodes	14	–	3.38	7.8	1.0	96.26	M+A	–	–	–	–	–
4	Coal-tar epoxy (C-200)	15	6.33	.70	0.9	0.6	95.99	16 (1.72)	14	8.2	0.53	2.1	0.21
22	Vinyl mastic/inorganic zinc-rich	16	4.00	1.42	0.9	1.7	95.42	46 (4.95)	13	7.6	0.24	0	1.40
19	Vinyl/inorganic zinc-rich	17	6.00	4.99	0.9	7.2	94.58	25 (2.69)	12	8.6	0.20	0.31	0.22
6	Coal-tar epoxy (Tarset)	18	6.67	1.44	1.5	1.4	93.40	16 (1.72)	17	7.7	0.80	2.9	0.72
21	Epoxy-tar/inorganic zinc-rich	19	4.67	1.23	0.7	1.5	92.56	15 (1.61)	–	–	–	–	–
8	Epoxy-tar (aluminum pigment)	20	7.33	0.63	0.3	0.8	91.94	21 (2.26)	4	8.9	0.07	0.03	0.06
11	Epoxy/inorganic zinc-rich	21	5.33	6.38	1.5	9.0	91.84	31 (3.34)	–	–	–	–	–
12	Saran	22	6.67	3.69	2.0	4.6	89.93	PVC	19	6.4	2.4	3.5	4.9
2	Bare carbon/zinc anodes	23	–	8.34	16.4	4.0	86.92	A	–	–	–	–	–
3	Bare carbon/aluminum anodes	24	–	10.32	28.0	0.8	82.13	A	–	–	–	–	–
23	Bare mariner steel	25	–	18.37	23.5	15.6	81.91	M	–	–	–	–	–
1	Bare carbon steel	26	–	28.23	32.0	26.2	77.05	–	20	–	6.0	12.2	9.7

*SI conversion factor: 1 mil = 0.0254 mm.

**Under cost, A refers to additional costs from anodes (20¢ extra per sq ft. [$2.15/m²]), M is for mariner steel (10¢ extra per sq ft [$1.08/m²]), + is for the aluminum oxide armor, and PVC is no longer available and cannot be figured into the cost.

***The average visual rating for the Dam Neck site was obtained from J. R. Lesnick, *Condition of Test Piles After 5 years of Exposure at Dam Neck, VA*, Interim Report (Coastal Engineering Research Center, 1976), and the rank and corrosion rates were taken from A. D. Hunter and C. H. Horton, *Underwater Engineering* (November 15, 1960).

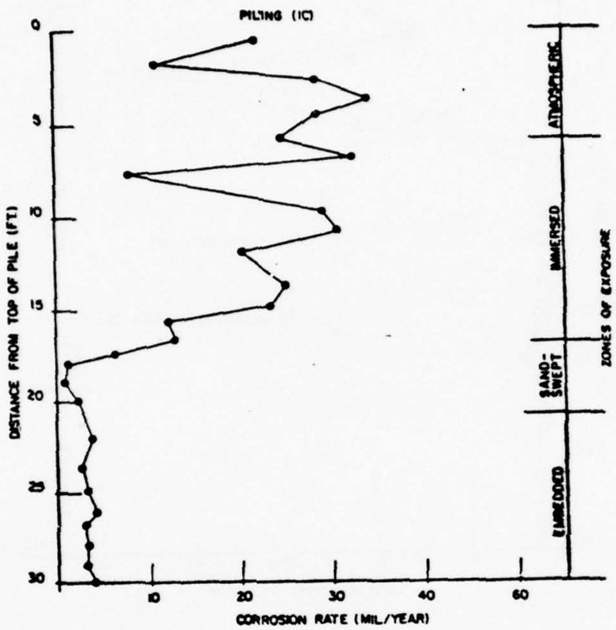

Figure 15. Corrosion profile of bare carbon steel. SI conversion factors: 1 ft = 0.3048 m; 1 mil = 0.0254 mm.

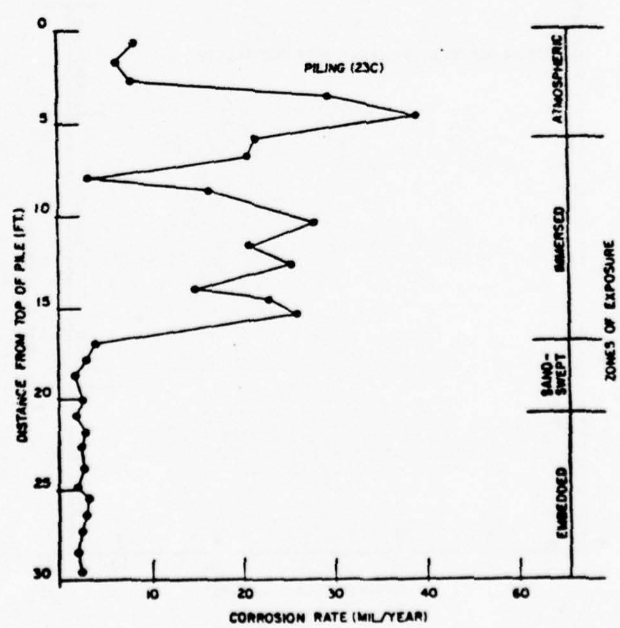

Figure 16. Corrosion profile of bare mariner steel. SI conversion factors: 1 ft = 0.3048 m; 1 mil = 0.0254 mm.

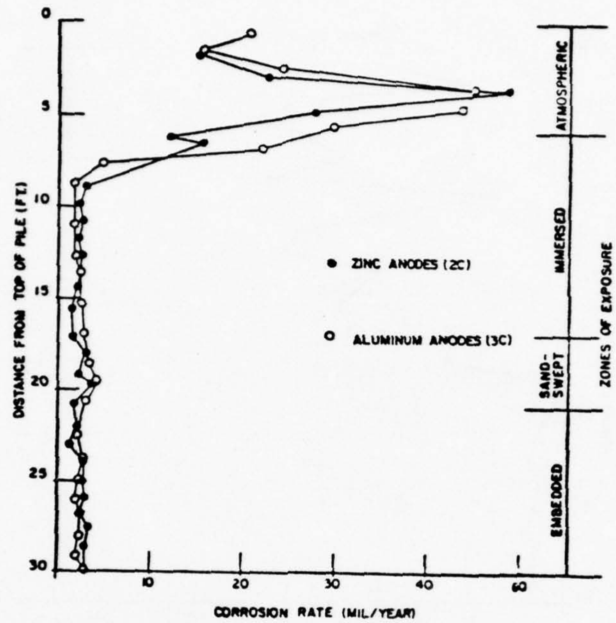

Figure 17. Corrosion profile of cathodically protected bare carbon steel. SI conversion factors: 1 ft = 0.3048 m; 1 mil = 0.0254 mm.

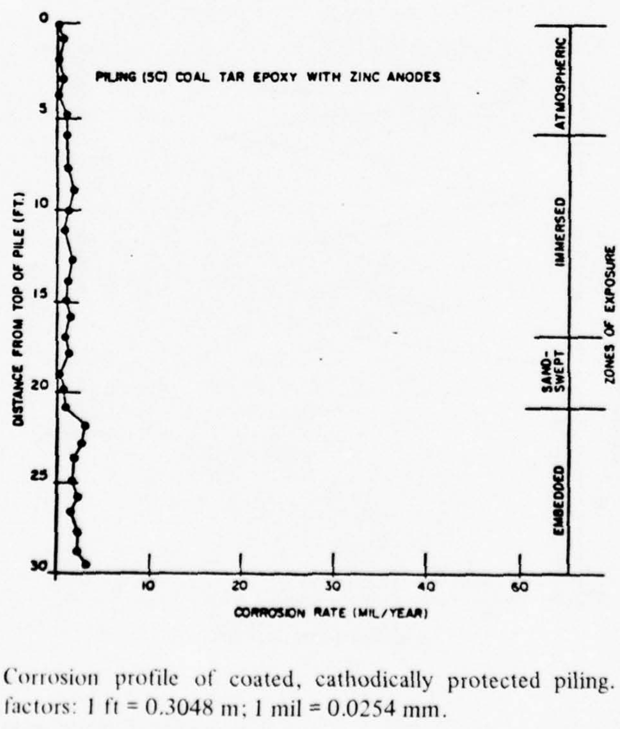

Figure 18. Corrosion profile of coated, cathodically protected piling. SI conversion factors: 1 ft = 0.3048 m; 1 mil = 0.0254 mm.

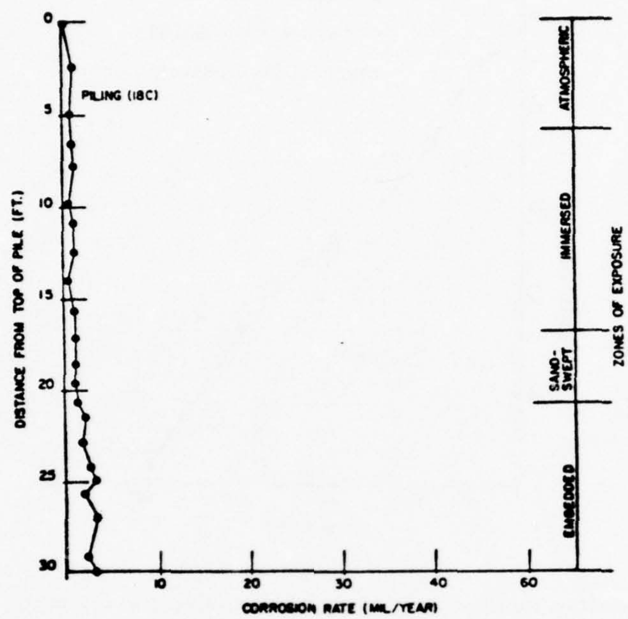

Figure 19. Corrosion profile of coal-tar epoxy over organic zinc-rich primer. SI conversion factors: 1 ft = 0.3048 m; 1 mil = 0.0254 mm.

Table 15

Physical Characteristics of LaCosta Island and Dam Neck Sites*

	LaCosta	Dam Neck
Mean yearly temp.	75°F (24°C)	58°F (14°C)
Mean salinity	33 ppt	26.8 ppt
Mean tide level	1.3 ft (0.4 m)	1.7 ft (0.5 m)
Spring tide range	2.6 ft (0.8 m)	4.1 ft (1.2 m)
Wave action	Light breakers	Heavy breakers

**Coast and Geodetic Survey Pub. 31-1*, 4th ed. (U. S. Department of Commerce, 1972).

immersed and atmospheric zones; the difference in corrosion rate is not great enough to justify use of the mariner steel alone as a means of corrosion prevention.

The use of zinc and aluminum anodes reduces corrosion in the immersed zone, but has little effect on corrosion in the atmospheric zone, because the sacrificial protection mechanism is only operative in the immersed zone.

The addition of a coating to a cathodically protected system reduces the corrosion in the atmospheric zone. The corrosion profile of a coated, cathodically protected pile is nearly identical to the profile of a coated pile providing equivalent protection. The advantage of the coated, cathodically protected system is its capability to protect the steel when damage to the coating in the immersion zone occurs. This should extend the long-term life of the system.

The rate of consumption of the zinc and aluminum anodes applied to the bare pilings at LaCosta Island was found to be 1.6 and 0.8 lb/year (0.7 and 0.4 kg/year), respectively. Figures 20 and 21 show the pit distribution for the respective anodes; the average pit depth was on the order of 0.25 in. (6.4 mm) for both anodes.

The corrosion profiles constructed by Escalante, et al.[10] for the Dam Neck piles indicate similar behavior

[10]E. Escalante, et al., *Protection of Steel Piles in a Natural Seawater Environment–Part II*, NBSIR 76-1104 (National Bureau of Standards, 1976).

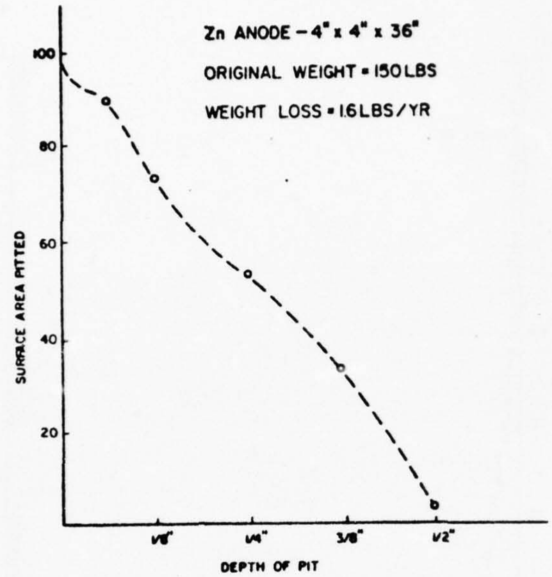

Figure 20. Pit distribution for zinc anodes. SI conversion factors: 1 in. = 2.54 cm; 1 lb = 0.4536 kg.

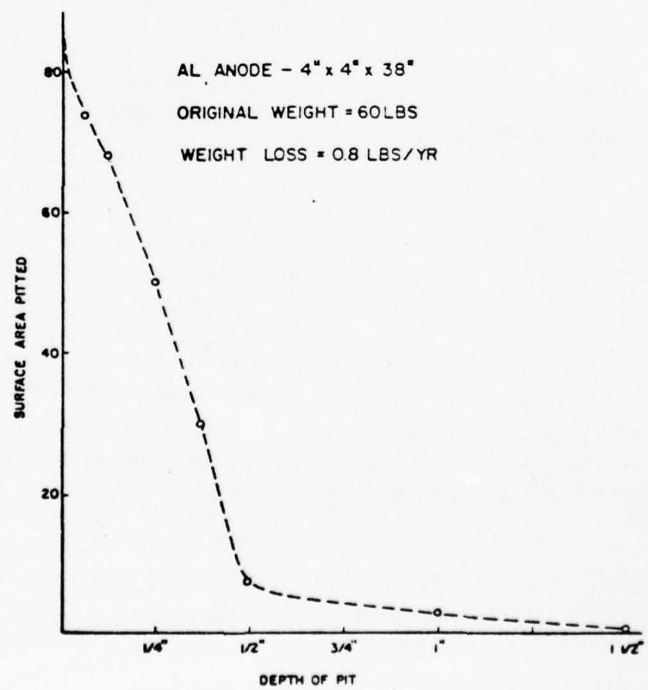

Figure 21. Pit distribution for aluminum anodes. SI conversion factors: 1 in. = 2.54 cm; 1 lb = 0.4536 kg.

to those of LaCosta Island. No comparison of cathodically protected systems can be made because no data for cathodically protected pilings from the Dam Neck system are available.

Figures 22 and 23 show the cathodic protection index[11] as a function of corrosion rate for the LaCosta Island and Dam Neck pilings, respectively. The data from both sites reveal sharp declines in CPI with increasing corrosion rate for each independent generic system. At low corrosion rates, the CPI appears to depend on the specific generic system, while high corrosion rates are associated with low CPI, regardless of the generic system. The bare steel baseline was included to indicate the low CPI coupled with the high corrosion rates generated by the bare steel, in comparison to any of the coating systems. The correlation between CPI and corrosion rate was determined by computer analysis to be 80 percent for all systems.

Data presently available from the Dam Neck site were used to analyze the behavior of corrosion current with respect to the corrosion rate, as shown in Figure 24. A computer analysis was conducted to determine the degree of correlation between corrosion current and corrosion rate. A strong correlation of 0.9 was found to exist. Since the corrosion current is determined by polarization measurements, this method provides a nondestructive testing technique of monitoring corrosion of steel immersed in water.

[11] *M. Romanoff, et al., "Protection of Steel Piles in a Natural Seawater Environment," Proceedings, Third International Congress on Marine Corrosion and Fouling* (1973).

6 CONCLUSIONS AND RECOMMENDATIONS

Conclusions

The following conclusions are based on the 5-year results:

1. Coal-tar epoxy over organic zinc-rich primer, polyester glassflake, and vinyl-sealed, flame-sprayed aluminum coatings performed excellently at both LaCosta Island, FL and Dam Neck, VA test sites.

2. Sacrificial anodes of zinc and aluminum effectively reduced the corrosion in the immersed zone from 26.2 mil/year (0.67 mm/year) to 4.0 and 0.8 mil/year (0.10 and 0.02 mm/year), respectively.

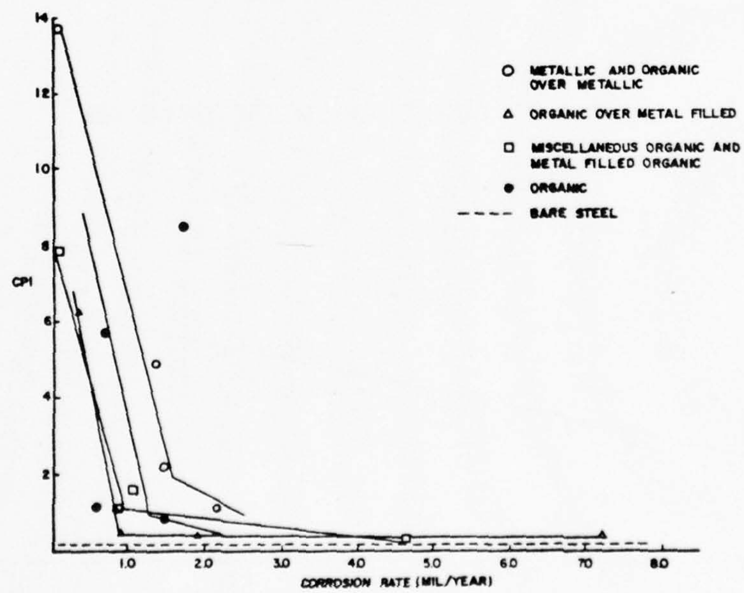

Figure 22. Cathodic protection index as a function of corrosion rate for LaCosta Island pilings. SI conversion factor: 1 mil = 0.0254 mm.

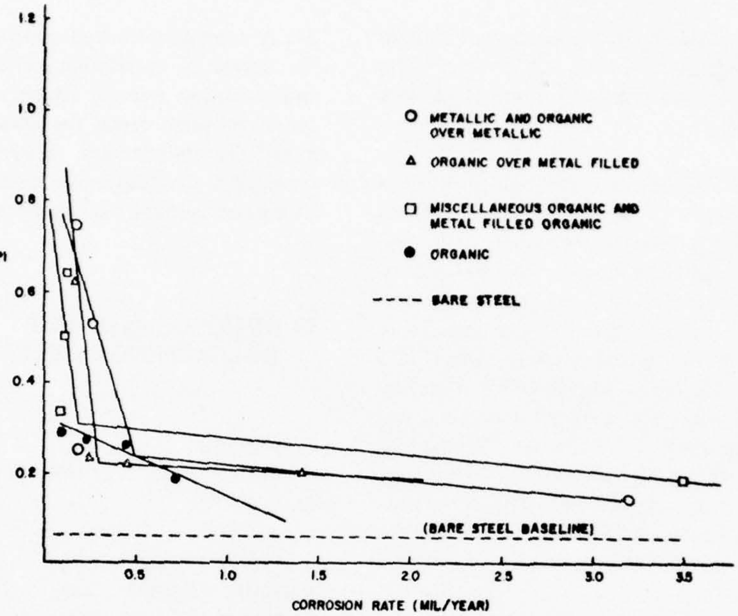

Figure 23. Cathodic protection index as a function of corrosion rate for Dam Neck pilings. CPI data were obtained from M. Romanoff, et al., "Protection of Steel Piles in a Natural Seawater Environment," *Proceedings, Third International Congress on Marine Corrosion and Fouling* (1973), and corrosion rates from E. Escalante, et al., *Protection of Steel Piles in a Natural Seawater Environment–Part II*, NBSIR 76-1104 (National Bureau of Standards, 1976). SI conversion factor: 1 mil = 0.0254 mm.

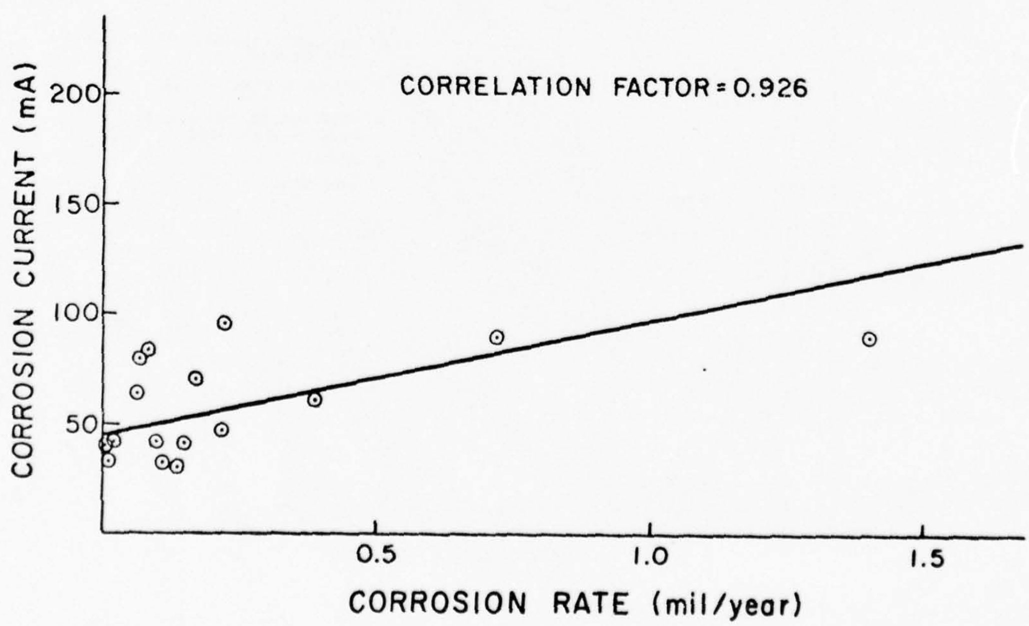

Figure 24. Corrosion rate vs. corrosion current. SI conversion factor: 1 mil = 0.0254 mm.

3. Coal-tar epoxy coating with zinc anodes for cathodic protection provides protection to the atmospheric zone and immersed zone and has the added capability of protecting the steel in the immersed zone should damage to the coating occur.

4. Electrochemical measurements of cathodic protection index and polarization current provide a powerful nondestructive testing technique for monitoring corrosion of steel immersed in water.

Recommendations

It is recommended that:

1. Zinc-rich primers be used as a means of reducing corrosion.

2. Sacrificial anodes be used as a means of providing cathodic protection to the immersed zone of coated or bare steel.

3. Use of the cathodic protection index and polarization measurement be continued for development as nondestructive testing techniques for monitoring corrosion of steel immersed in water.

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Schwerdtfeger, W. J. and O. N. McDorman, *Journal of the Electrochemical Society*, Vol 99 (1952), p 407.

APPENDIX A:

PHOTOGRAPHS OF CORROSION DAMAGE TO STEEL PILINGS AT LACOSTA ISLAND, FL

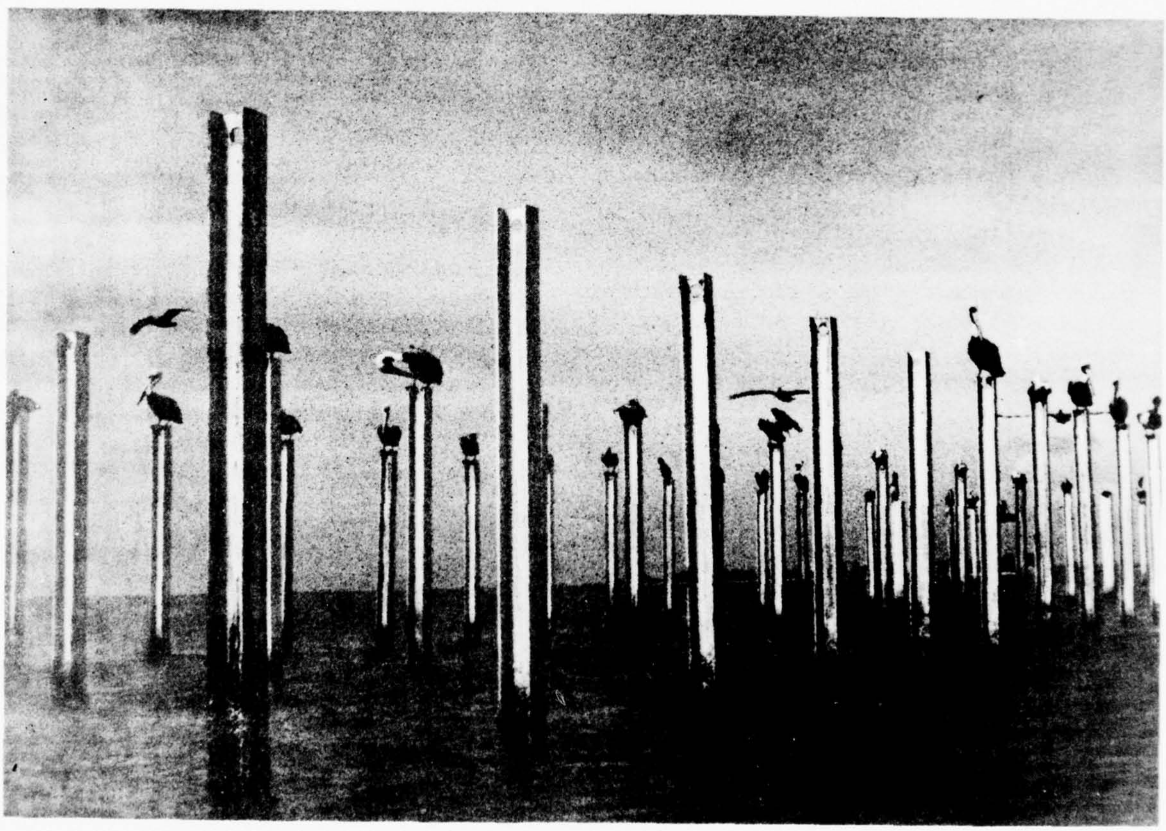


Figure A1. LaCosta Island piling test site.

Figure A2. Atmospheric zone of bare carbon steel with zinc anodes. Absence of protection against corrosion in the atmospheric zone is evident.

Figure A3. Atmospheric zone of bare carbon steel with aluminum anodes. Cathodic protection is only operative in the immersed zone, as seen from the damage present in the atmospheric zone of this pile.

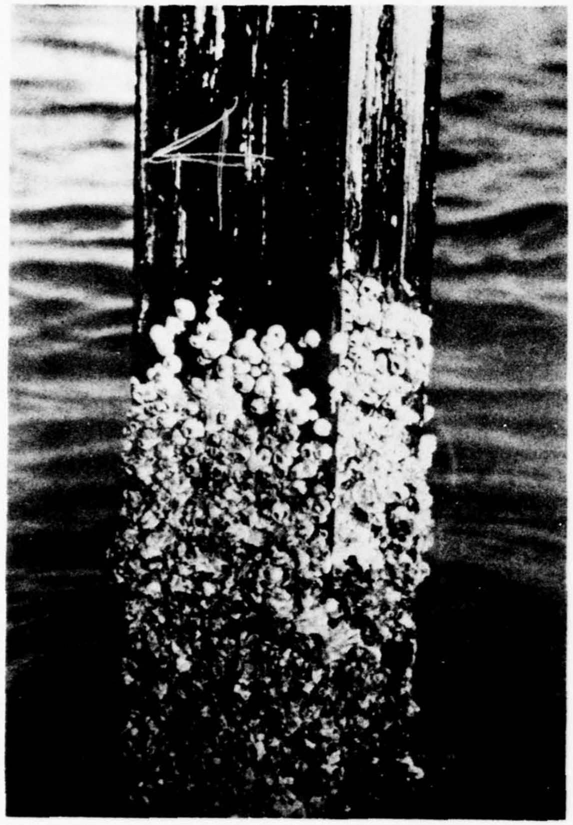


Figure A4. Coal-tar epoxy (C-200) on carbon steel. Photograph of upper immersed and lower atmospheric zones indicates the degree of marine fouling. Some damage to the flanges is also evident.

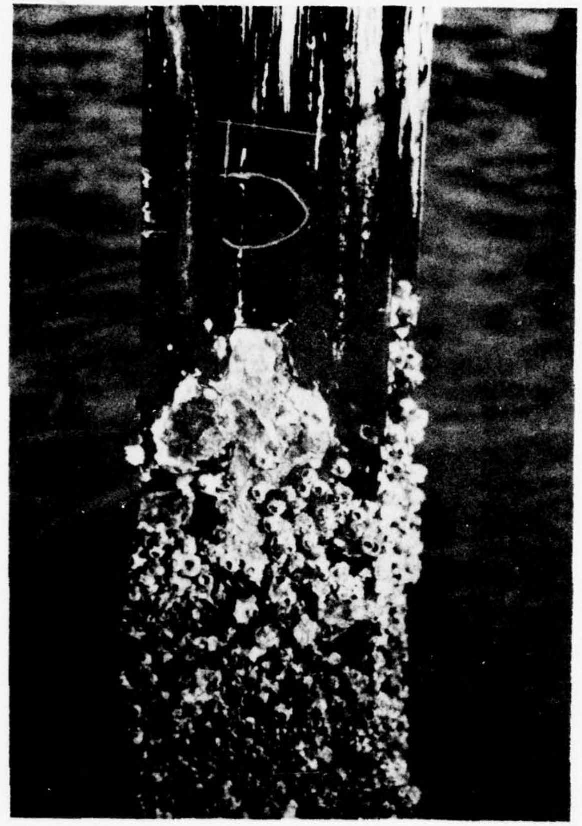


Figure A5. Coal-tar epoxy (C-200) with zinc anodes. Marine fouling is evident in the upper immersed zone, and some damage is present on the face of the pile in the atmospheric zone.

Figure A6. Bare carbon steel with zinc anodes after 5-year removal. Damage to atmospheric zone is evident.

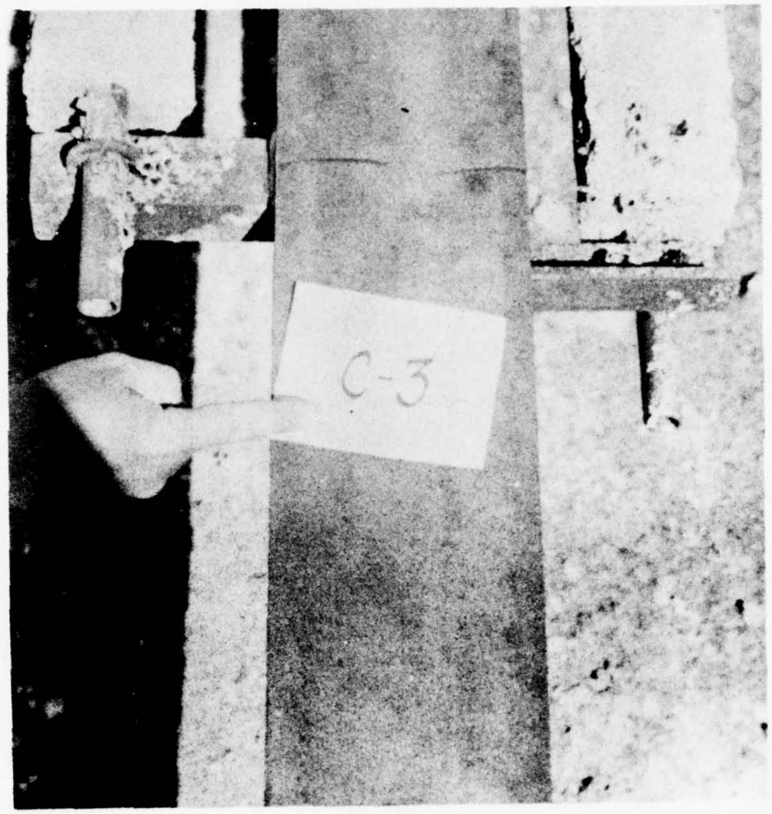


Figure A7. Bare carbon steel with aluminum anodes after 5-year removal. Protection afforded by sacrificial anodes is evidenced by lack of damage to immersed zone.

Figure A8. Typical fouling in the immersed zone.

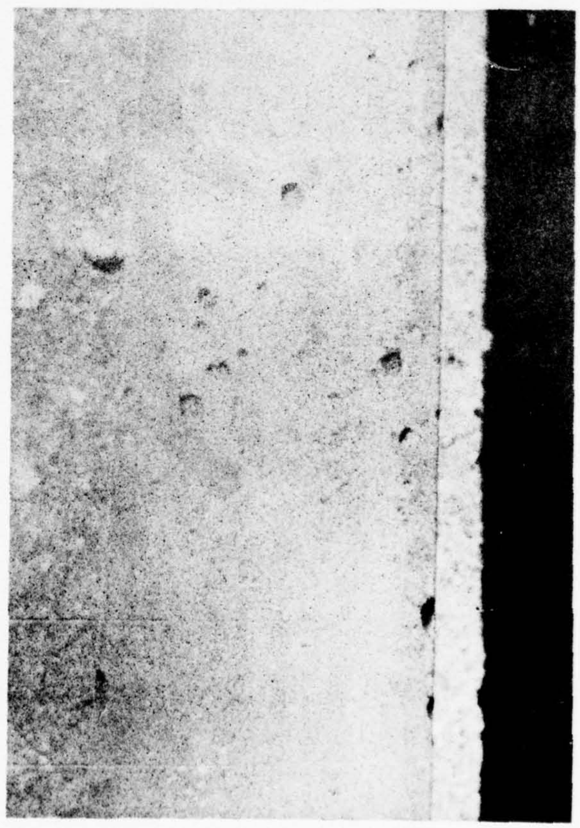


Figure A9. Aluminum-pigmented epoxy tar after sandblasting. Pitting is evidence of damage in the immersed zone.

Figure A10. Epoxy-tar over zinc-rich primer after sandblasting. Severe pitting in the immersed zone is indication of structural degradation caused by corrosion.

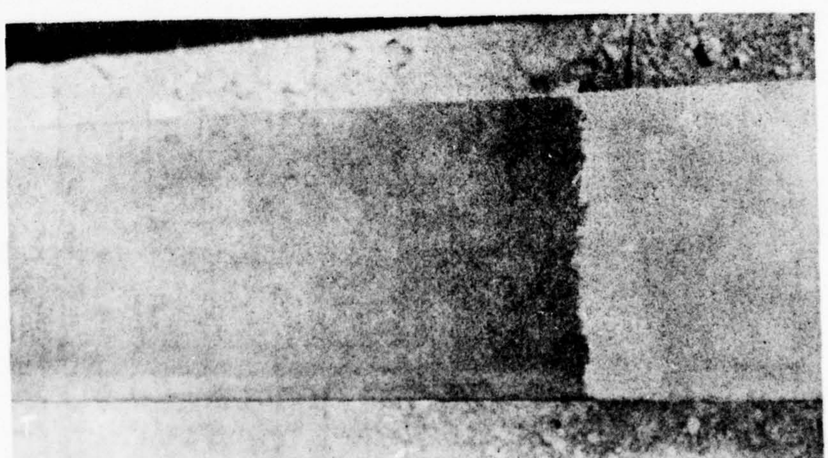
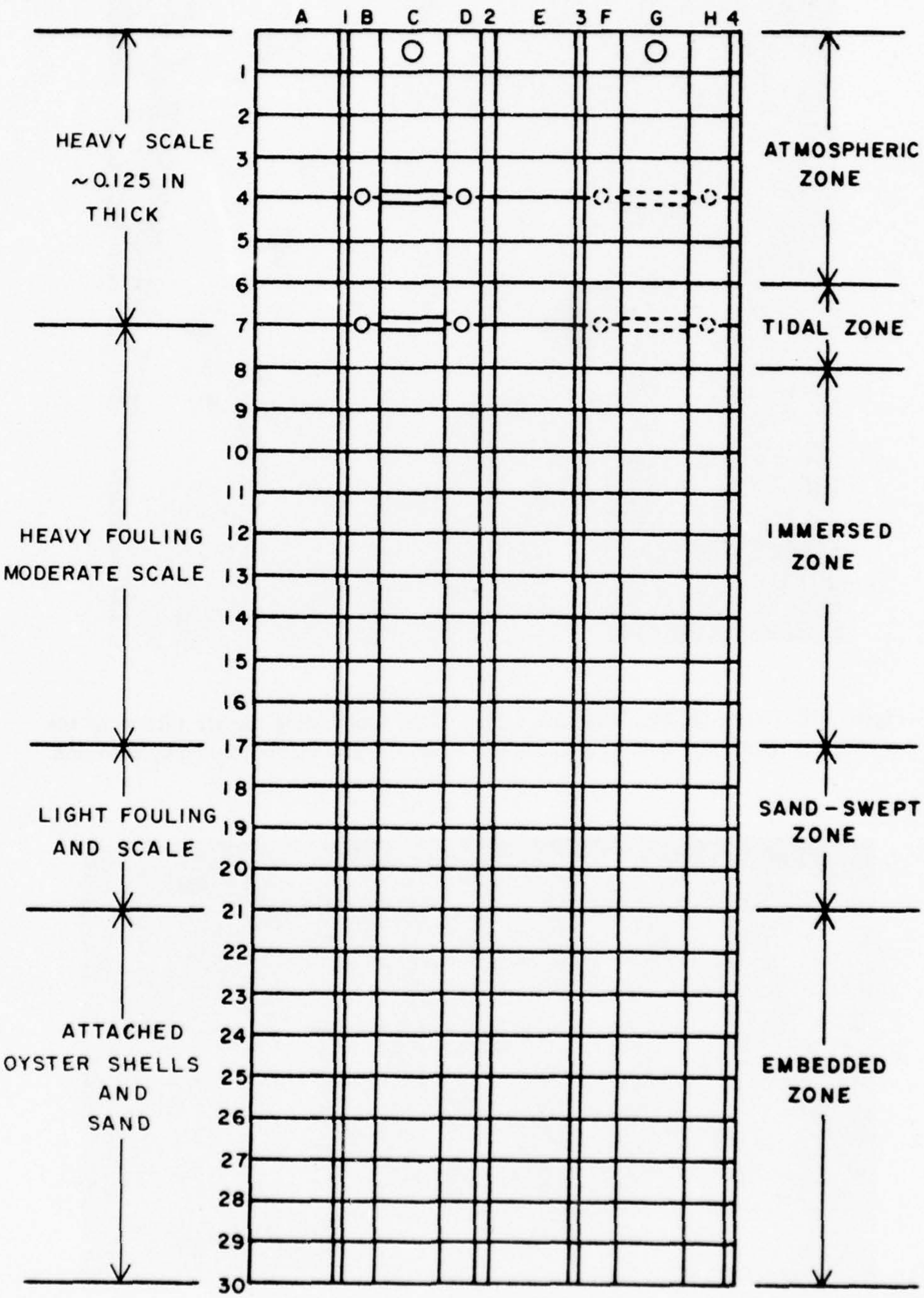


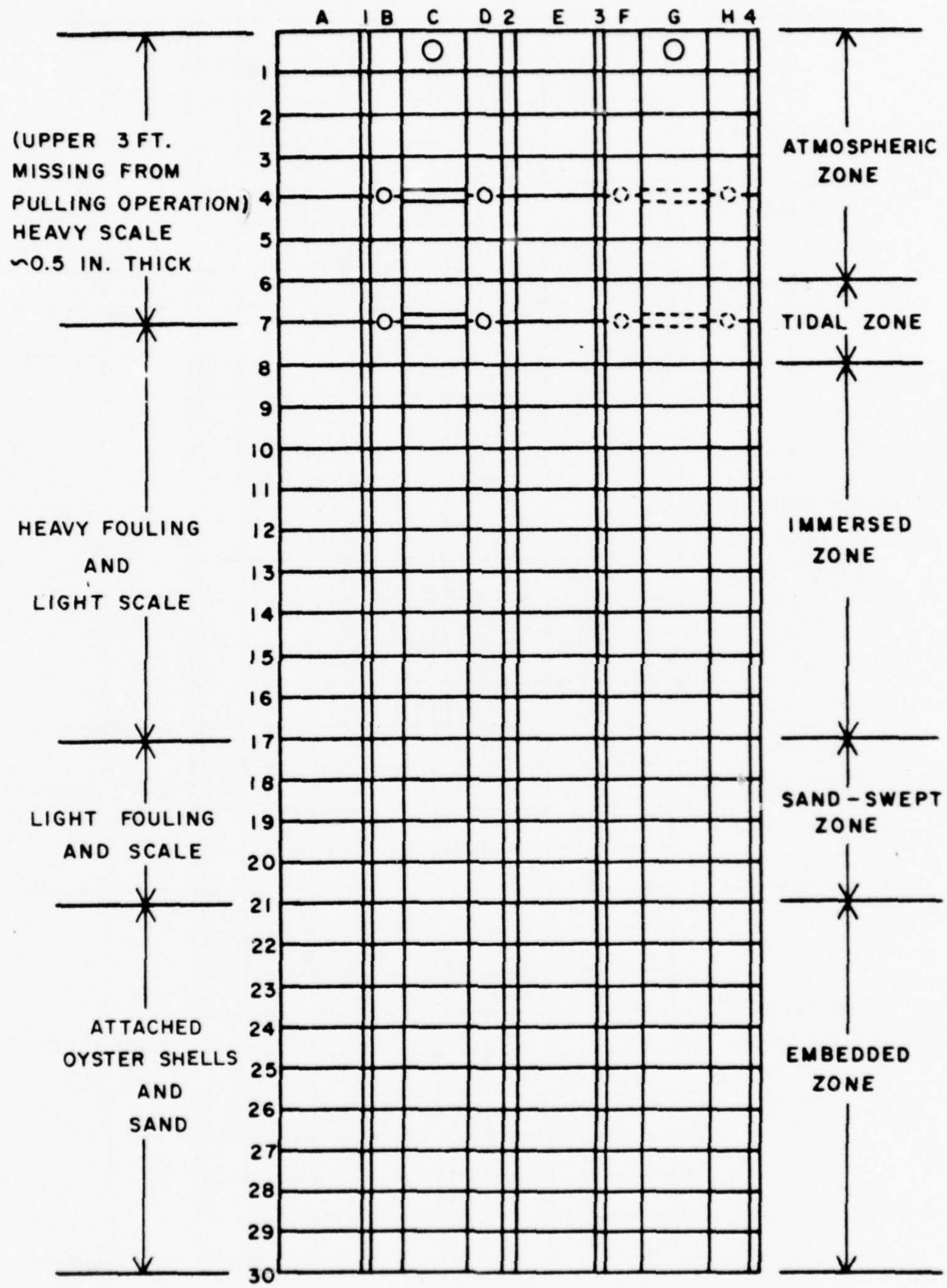
Figure A11. Polyester glassflake. Coating and steel after coating removal are in excellent condition in all zones.

APPENDIX B:

CHARTS OF CORROSION
BEHAVIOR OF STEEL PILINGS
AT LACOSTA ISLAND, FL

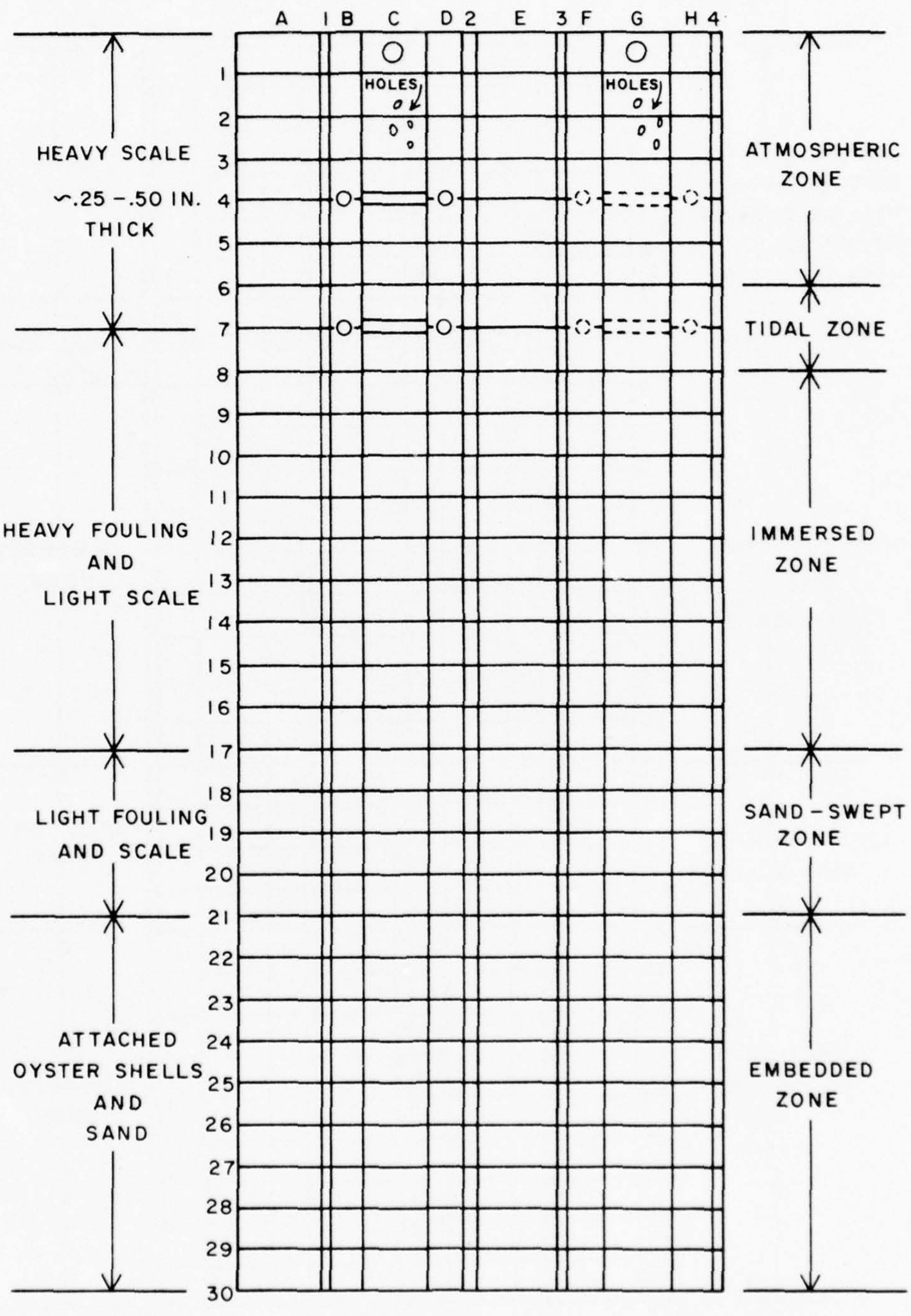


PILE NO. 1C
BARE CARBON STEEL

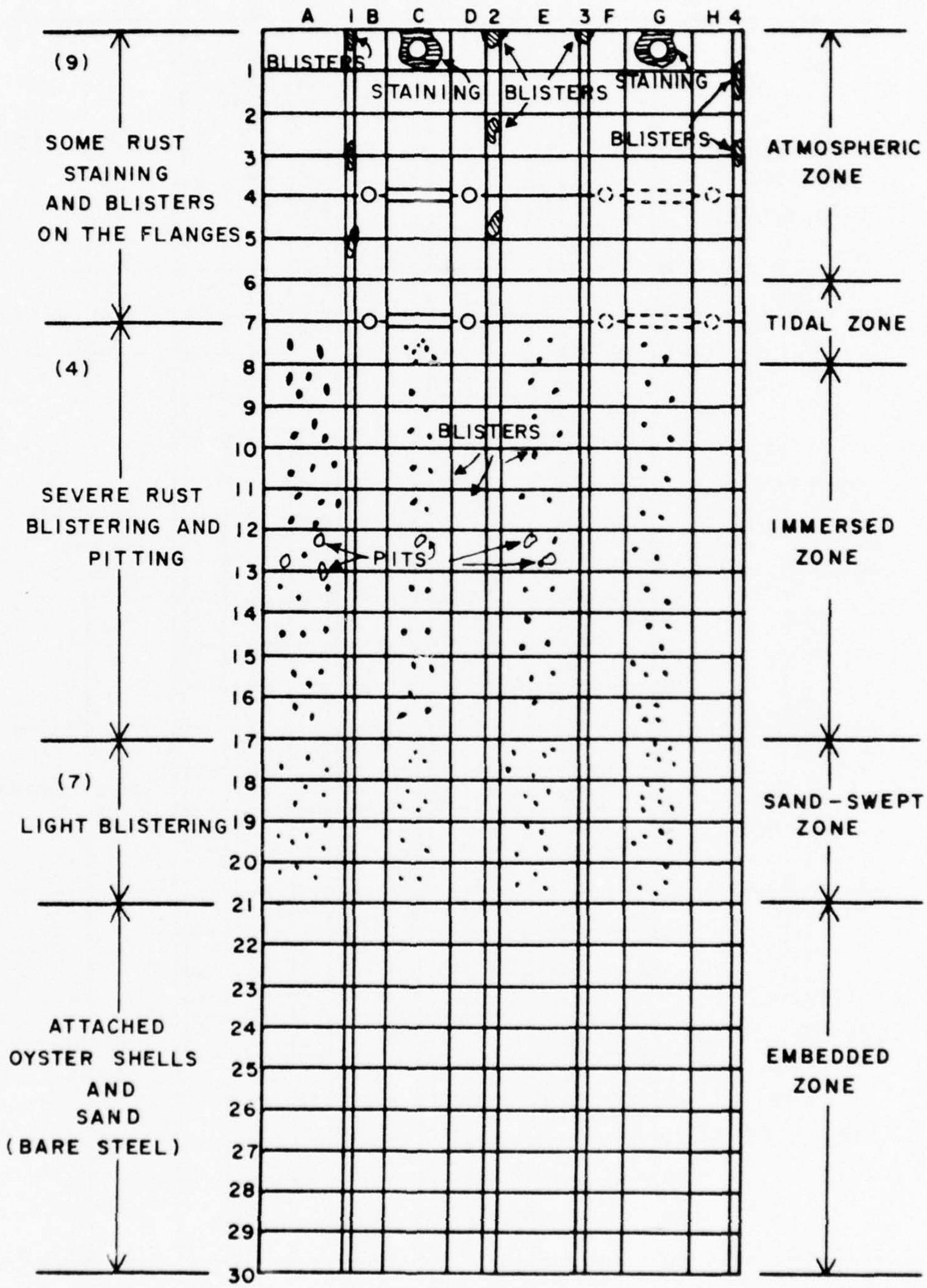


PILE NO. 2C

BARE CARBON STEEL W/ZINC ANODES

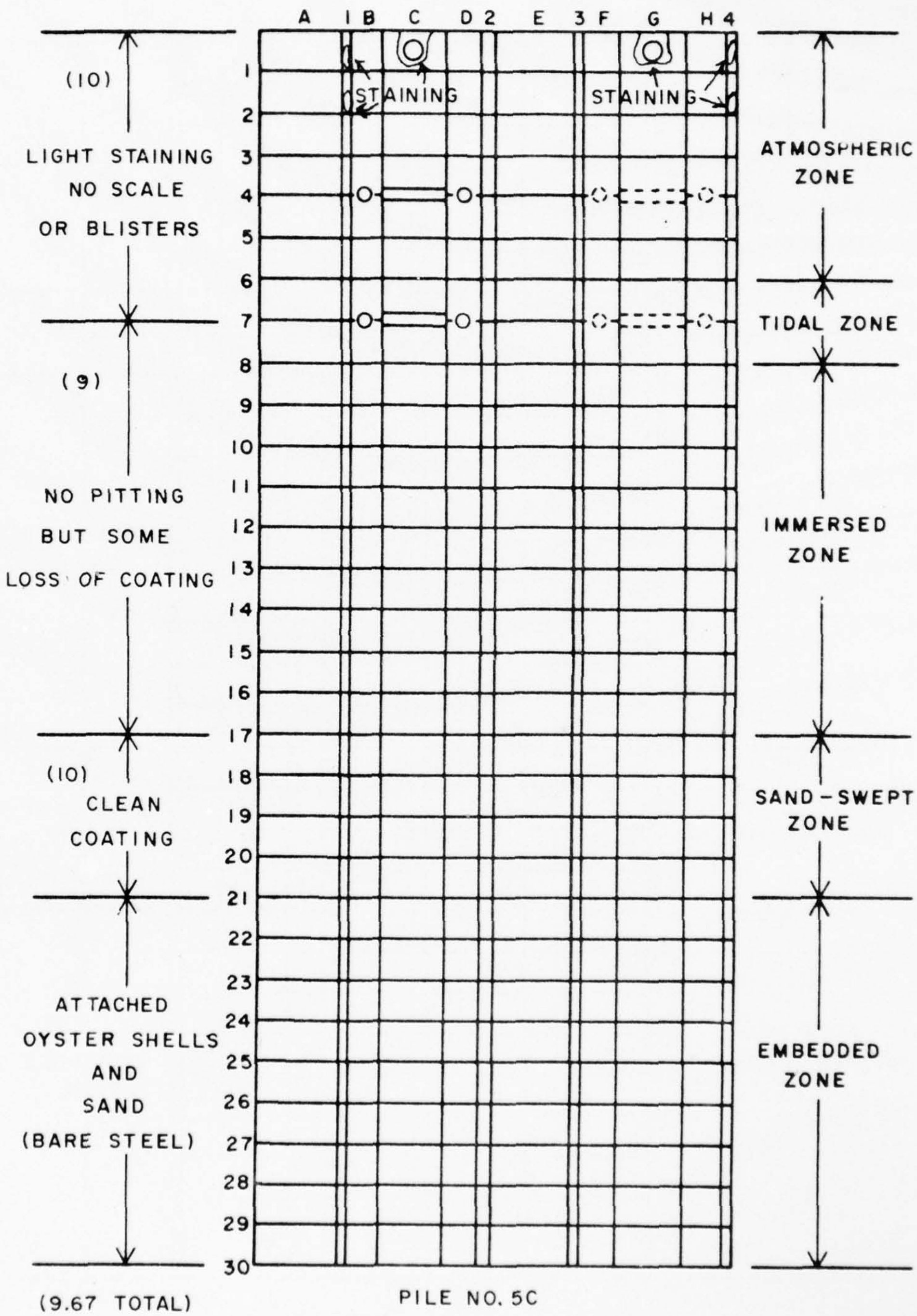


PILE NO. 3C
BARE CARBON STEEL **W/ALUMINUN ANODES**



PILE NO. 4C

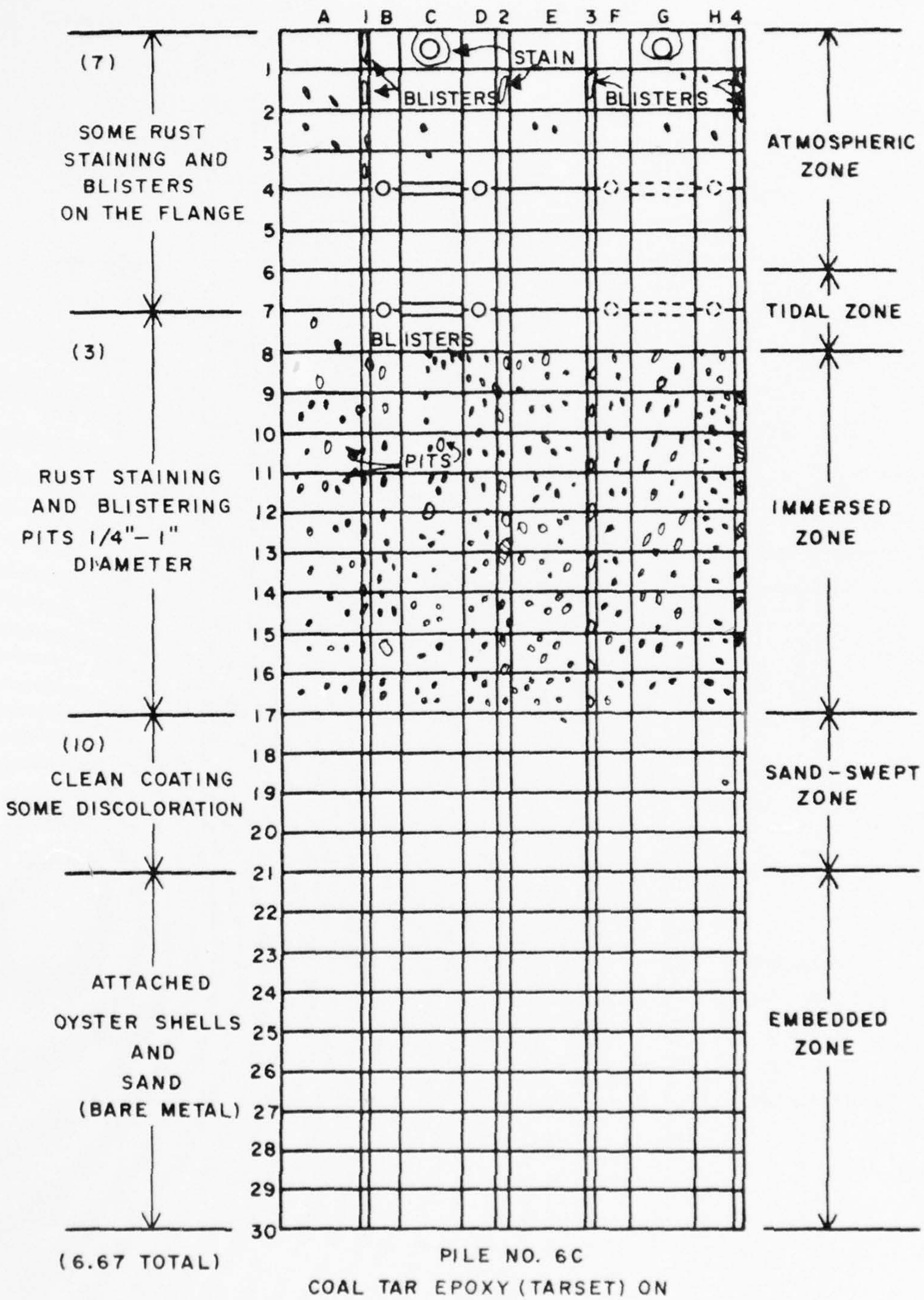
COAL TAR EPOXY (AMINE CURED)
ON CARBON STEEL



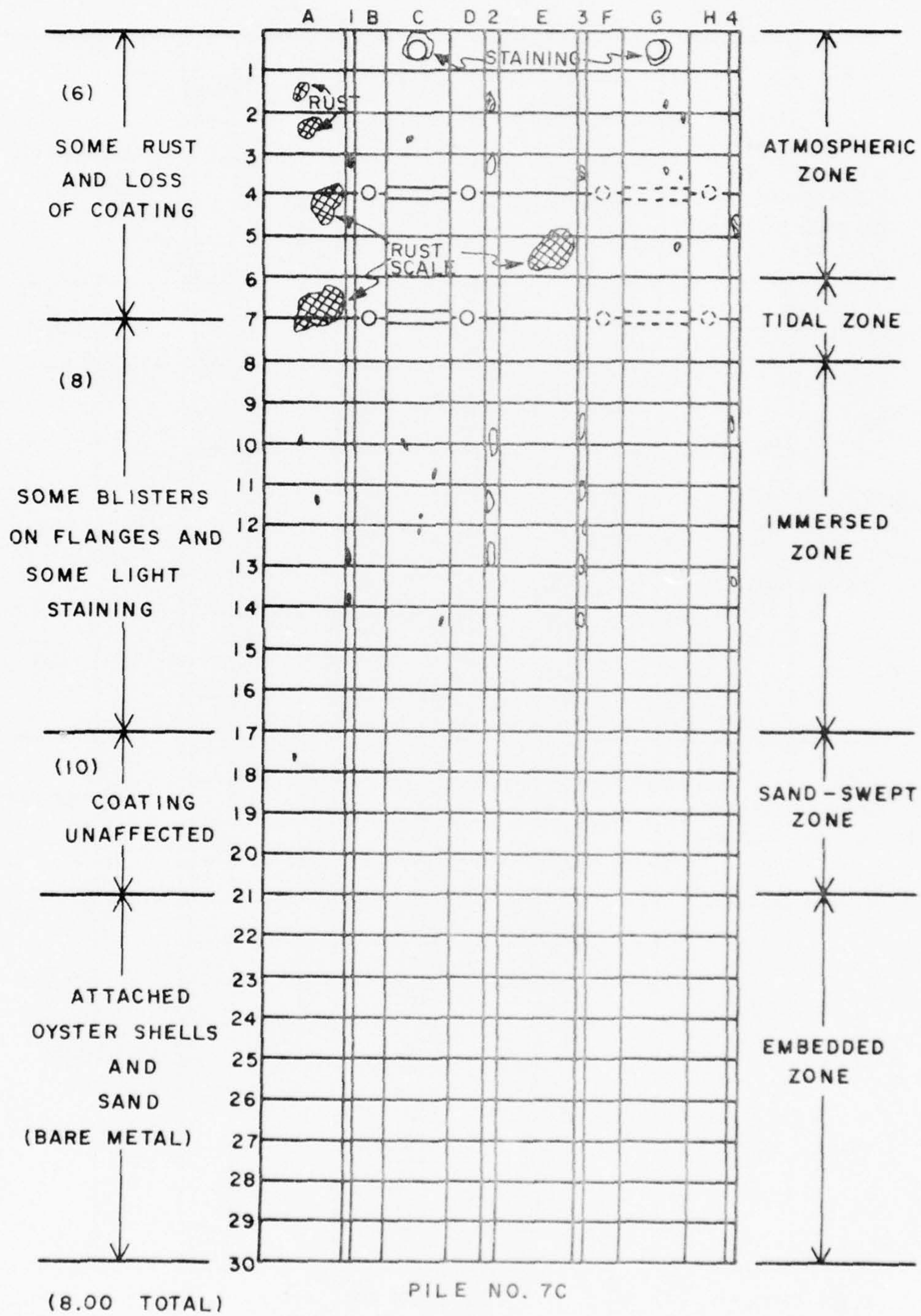
PILE NO. 5C

COAL TAR EPOXY ON CARBON STEEL

WITH ZINC ANODES



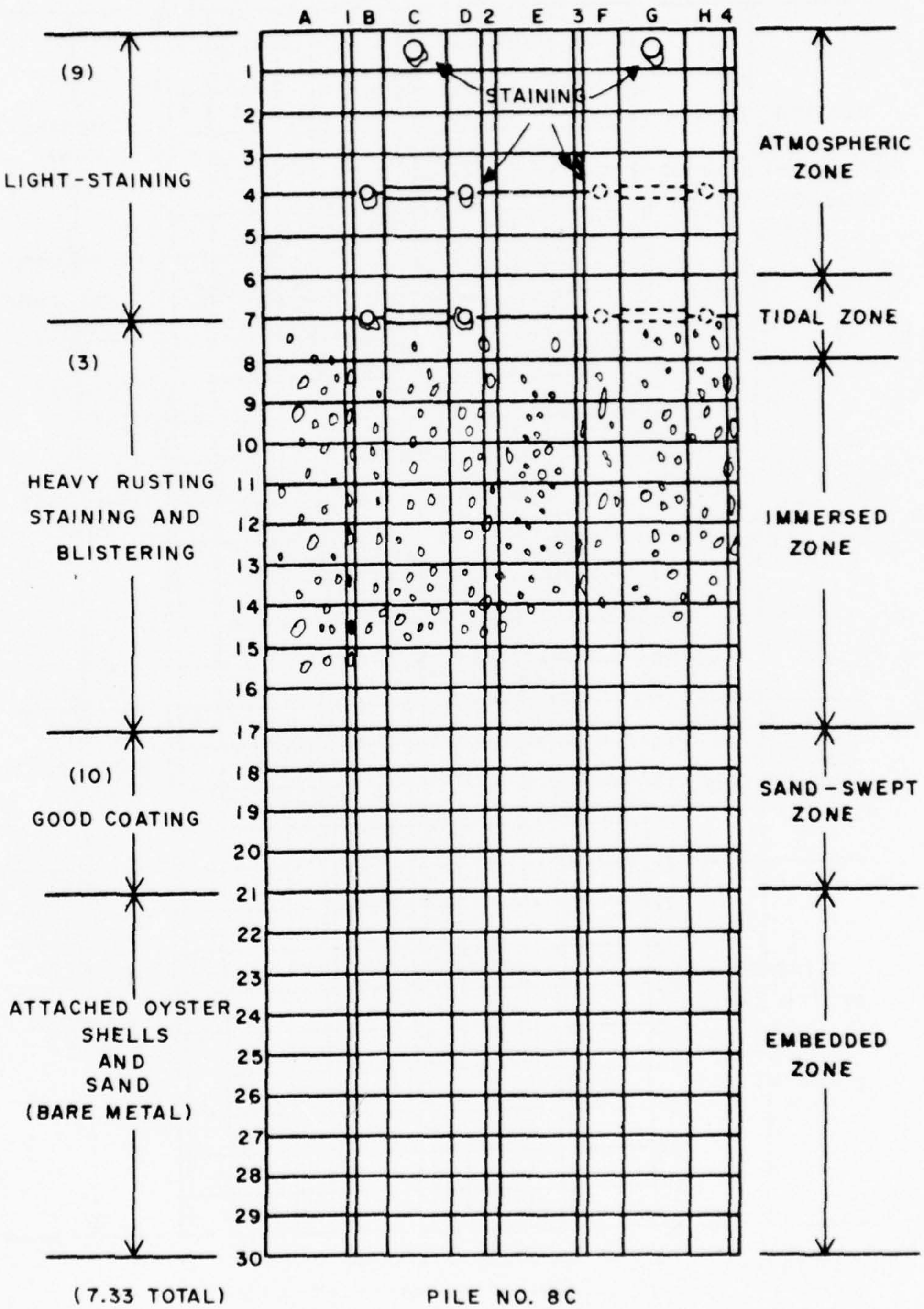
PILE NO. 6C
COAL TAR EPOXY (TARSET) ON
CARBON STEEL



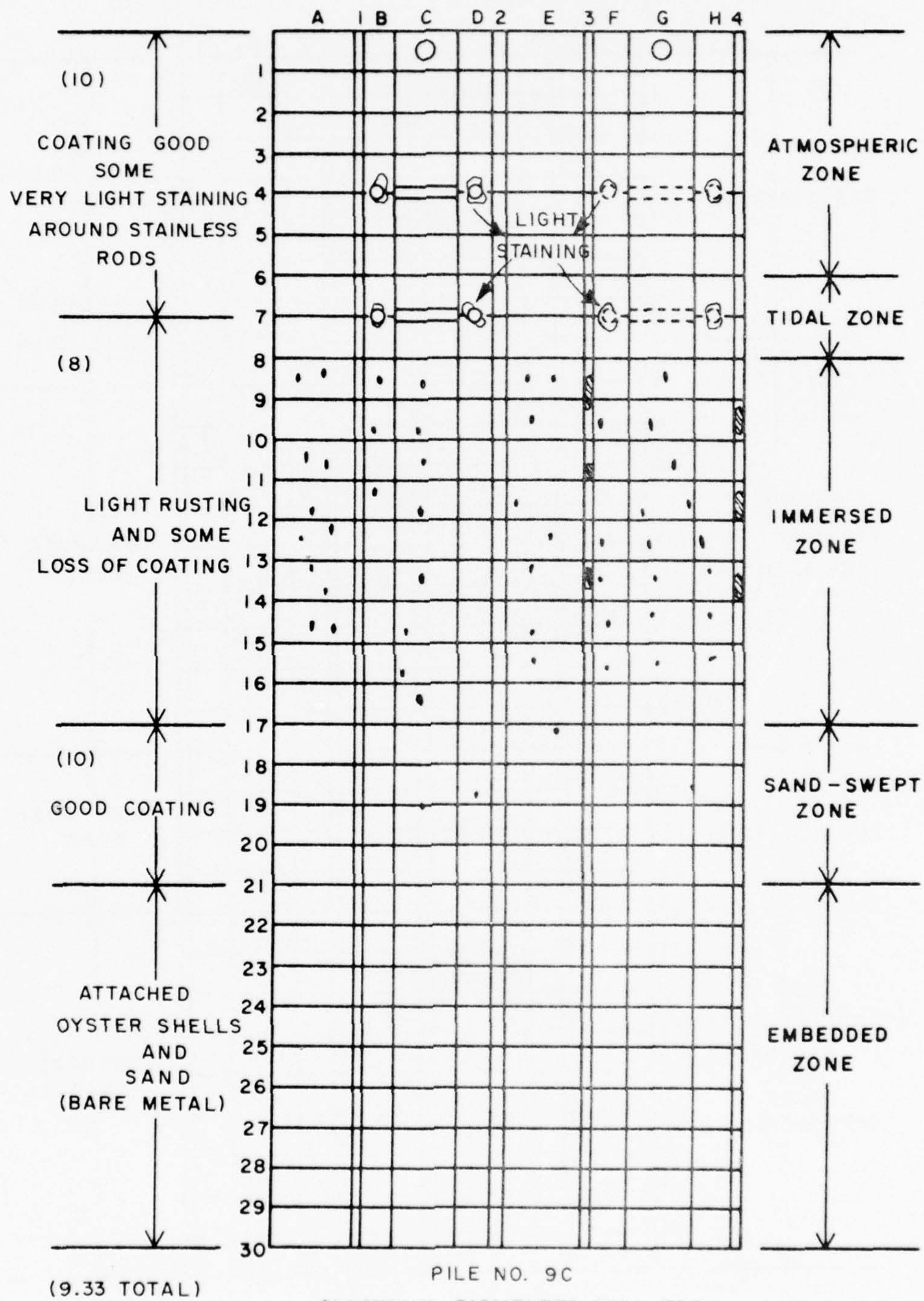
PILE NO. 7C

COAL TAR EPOXY (C-200) W/ALUMINUM OXIDE

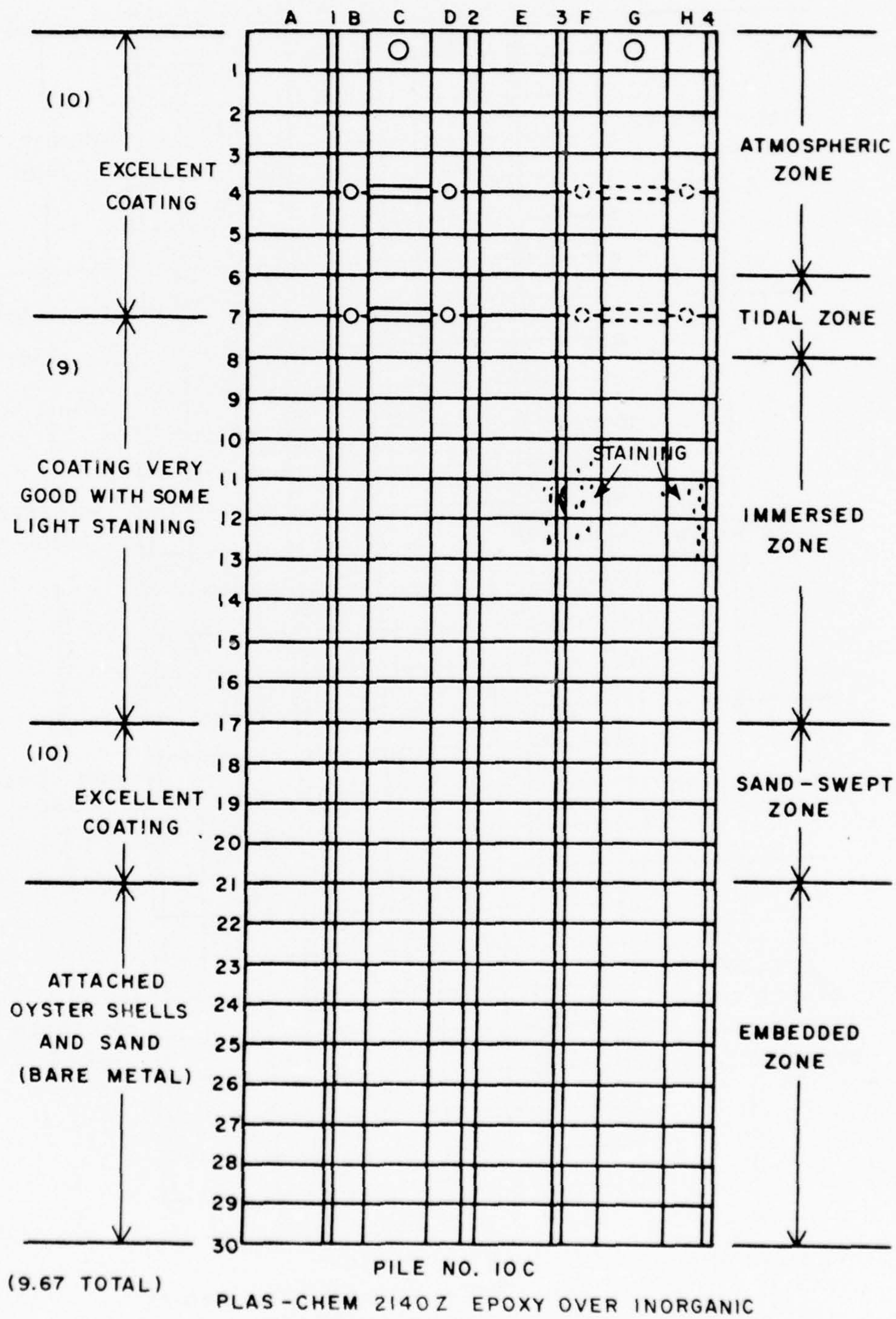
ARMOR AT THE MUD LINE



PILE NO. 8C
ALUMINUM PIGMENTED EPOXY-TAR
ON CARBON STEEL

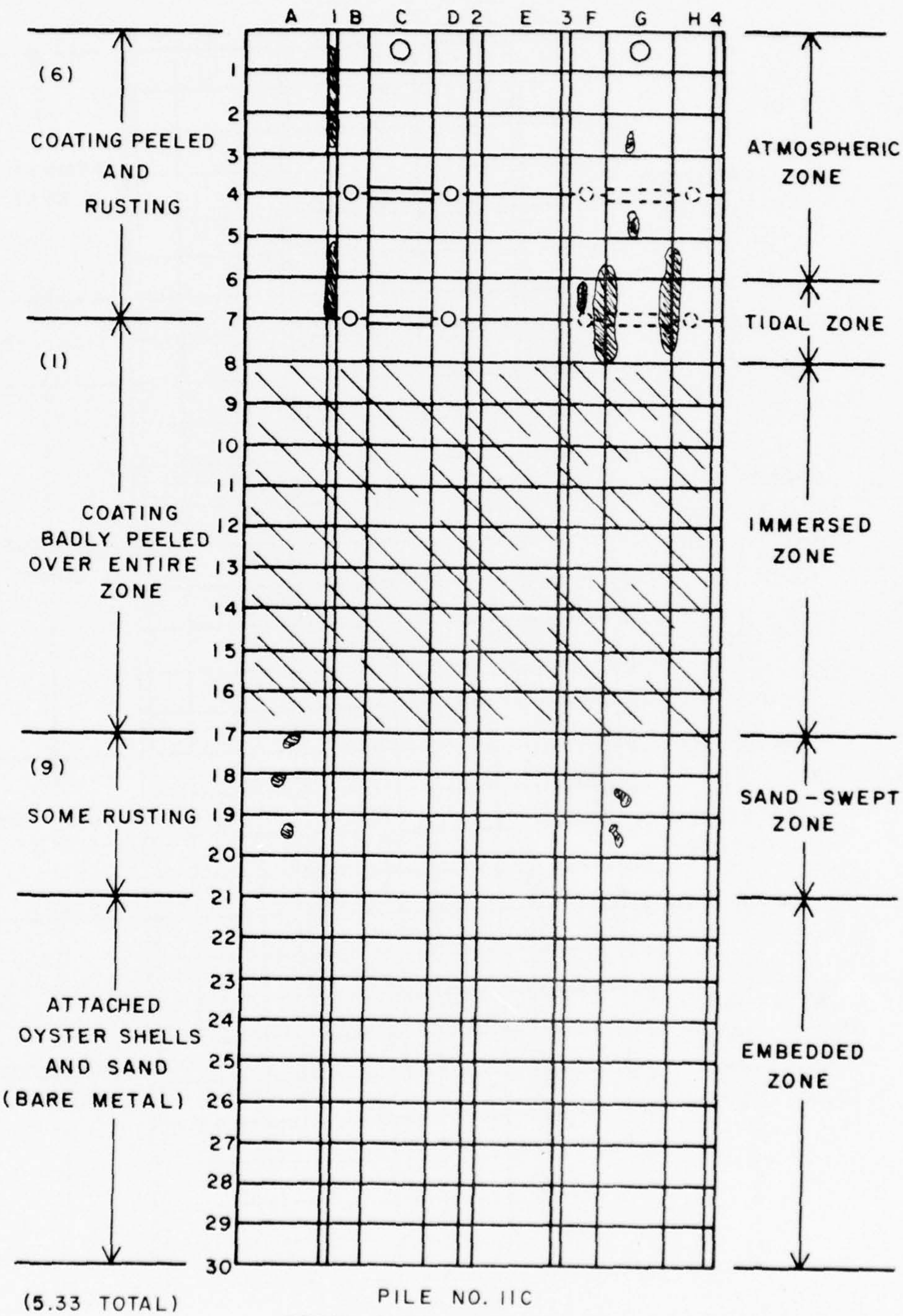


PILE NO. 9C
ALUMINUM PIGMENTED COAL TAR
(TARSET) EPOXY ON CARBON STEEL

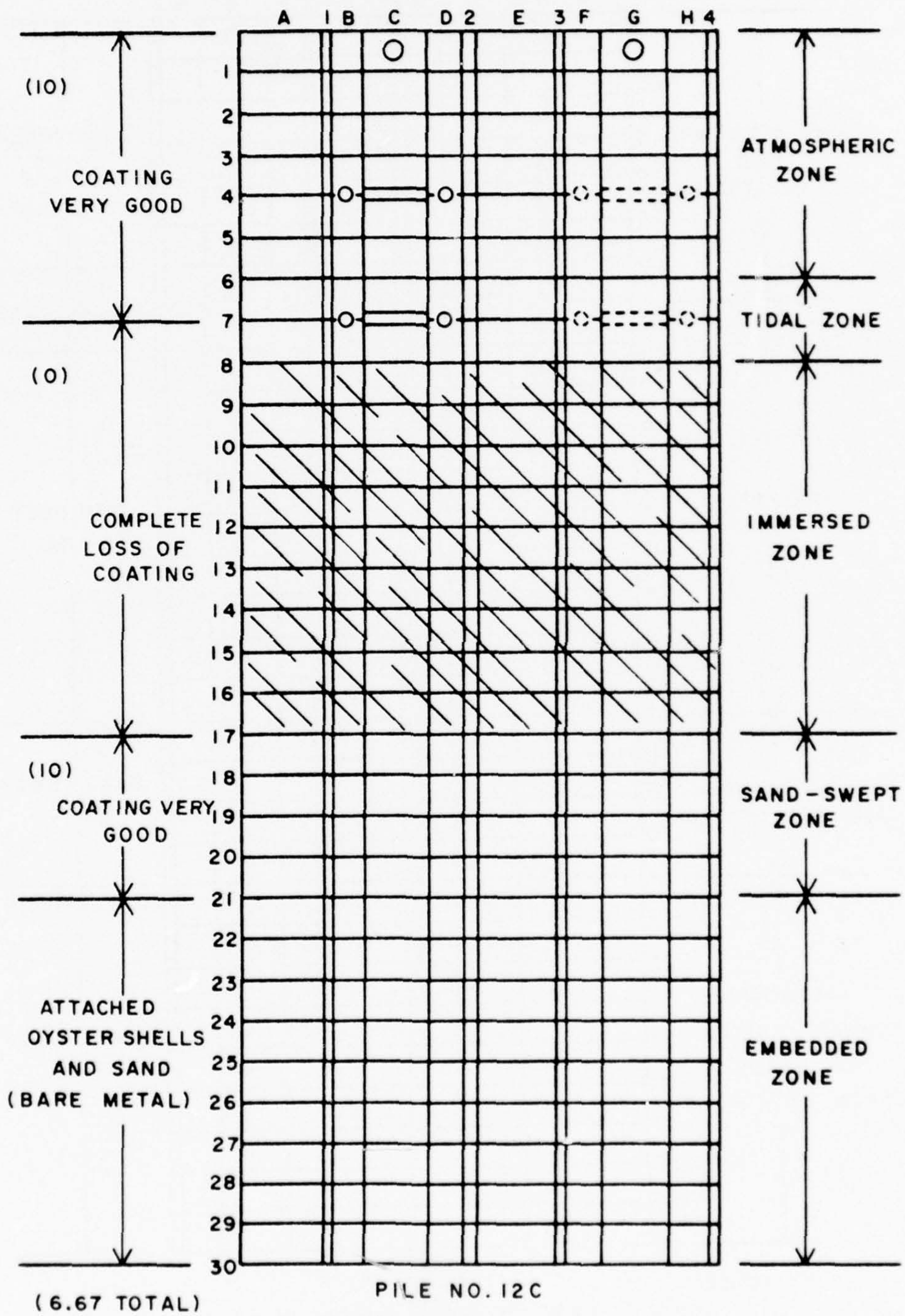


PILE NO. 10C

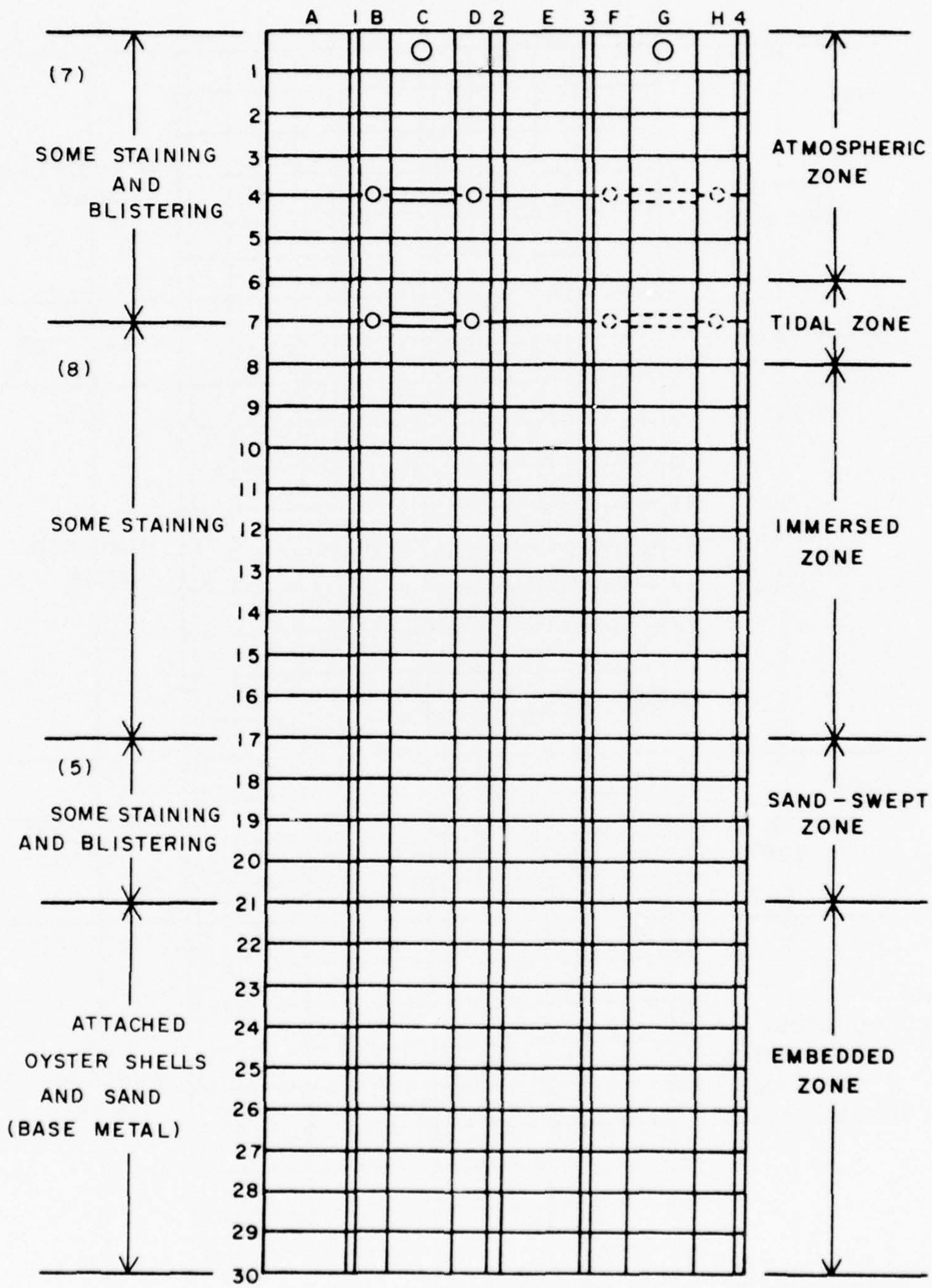
PLAS-CHEM 2140Z EPOXY OVER INORGANIC CERAM-ITE 101 W/ZINC-ITE B PRIMER



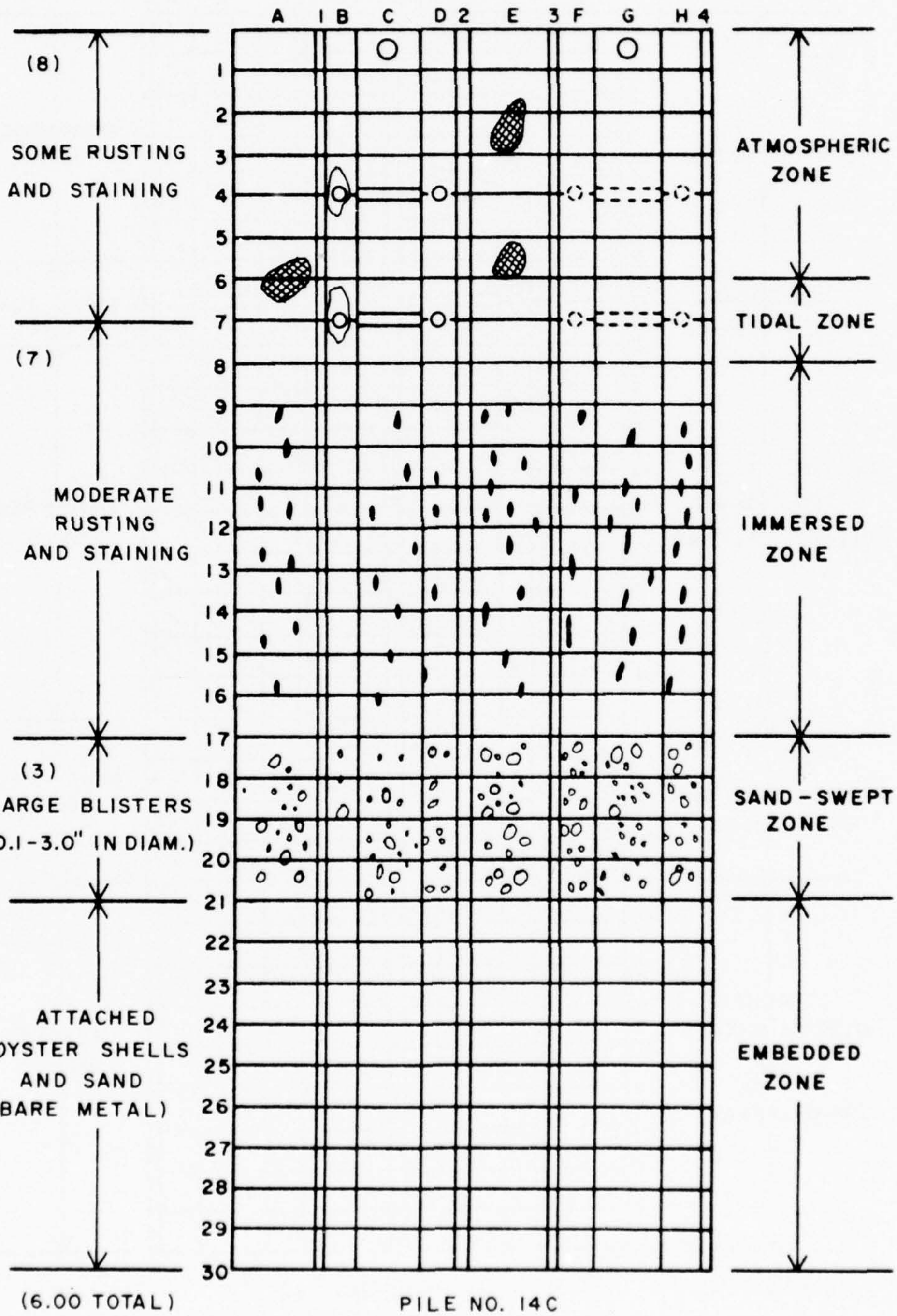
PILE NO. 11C
EPOXY OVER INORGANIC ZINC PRIMER
ON CARBON STEEL



PILE NO. 12C
SARAN FORMULA (NAVY STOCK)
ON CARBON STEEL



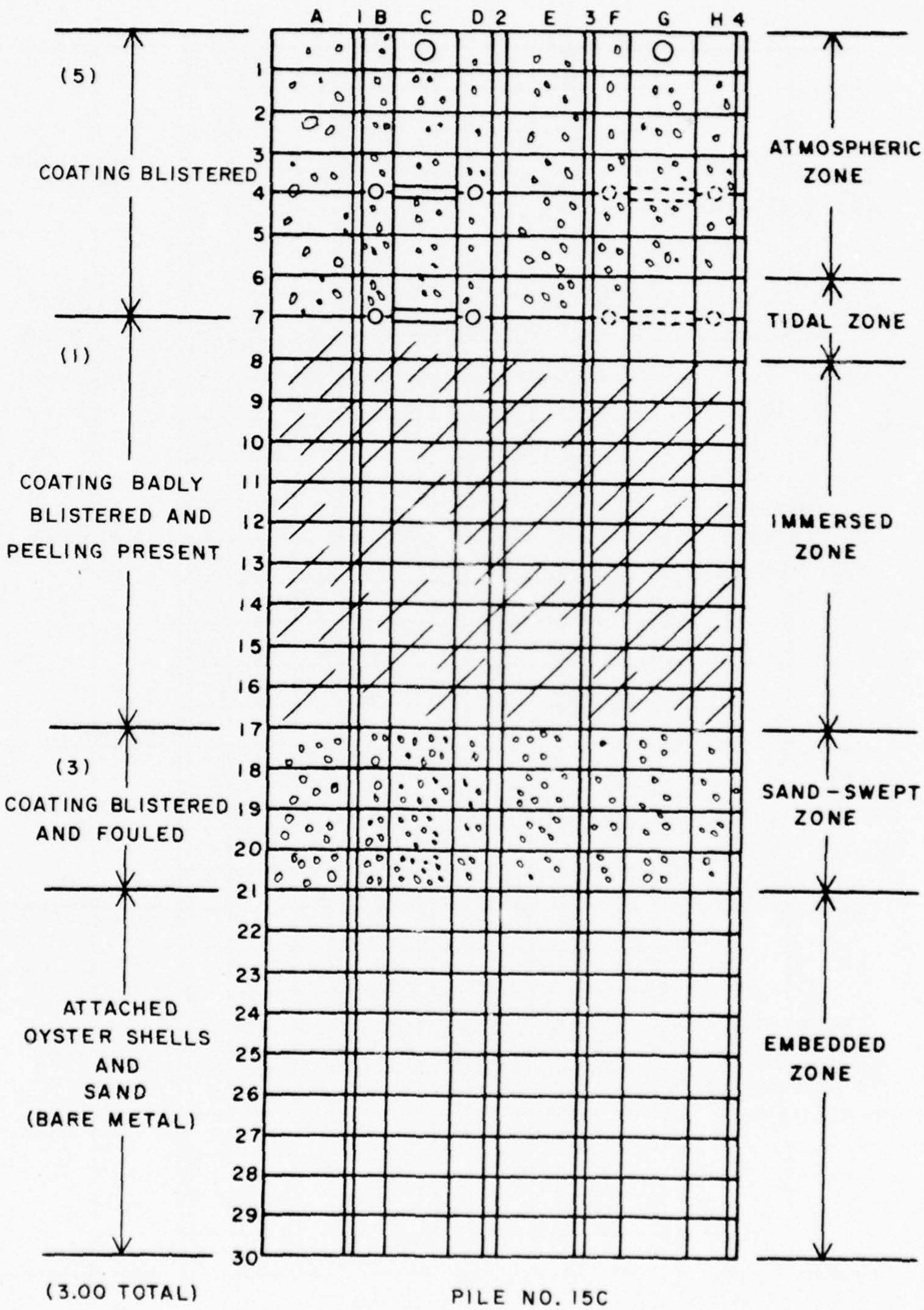
PILE NO. 13C
FLAME-SPRAYED ALUMINUM WIRE
ON CARBON STEEL



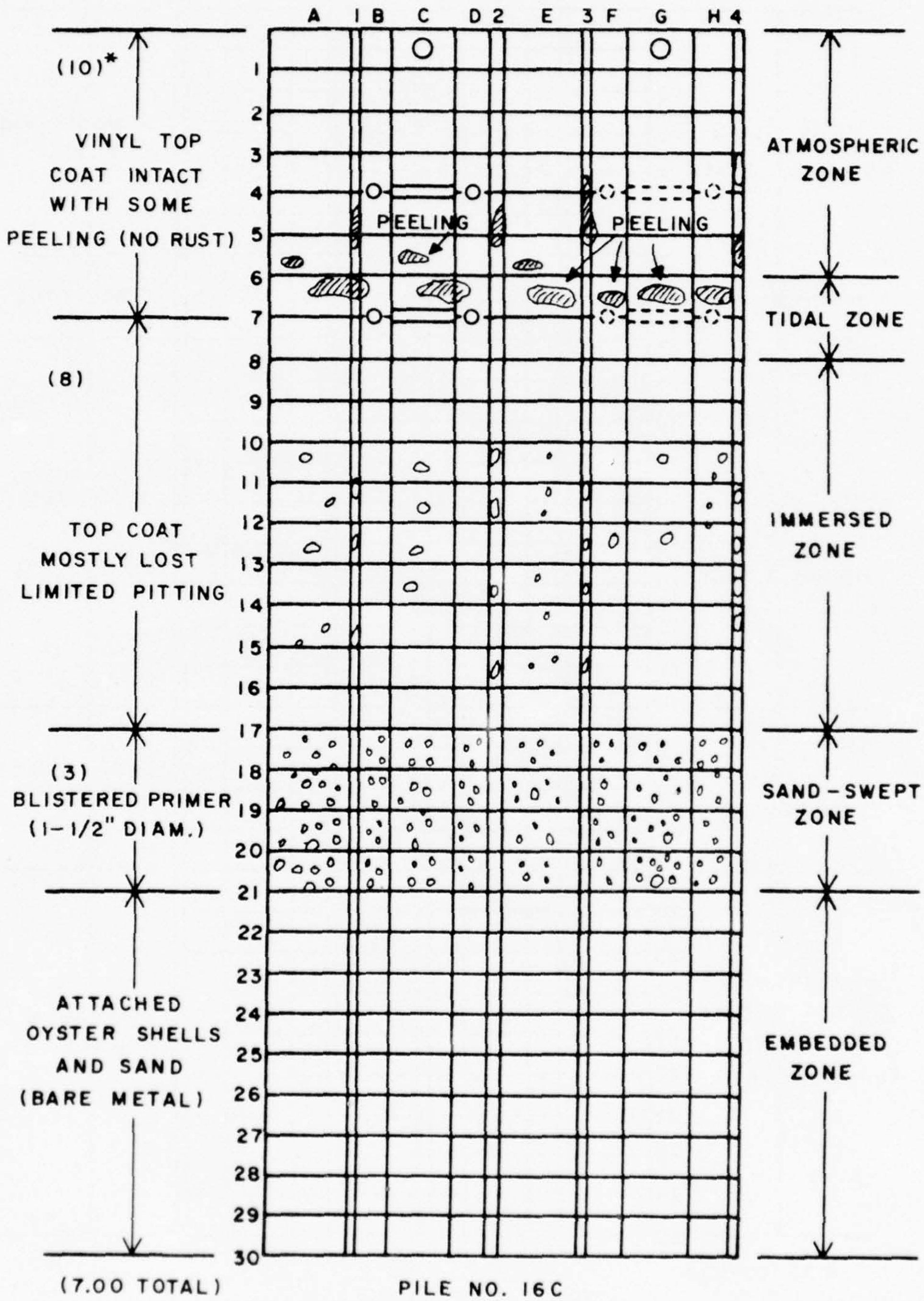
PILE NO. 14C

FLAME-SPRAYED ALUMINUM WIRE

W/VINYL TOPCOAT ON CARBON STEEL



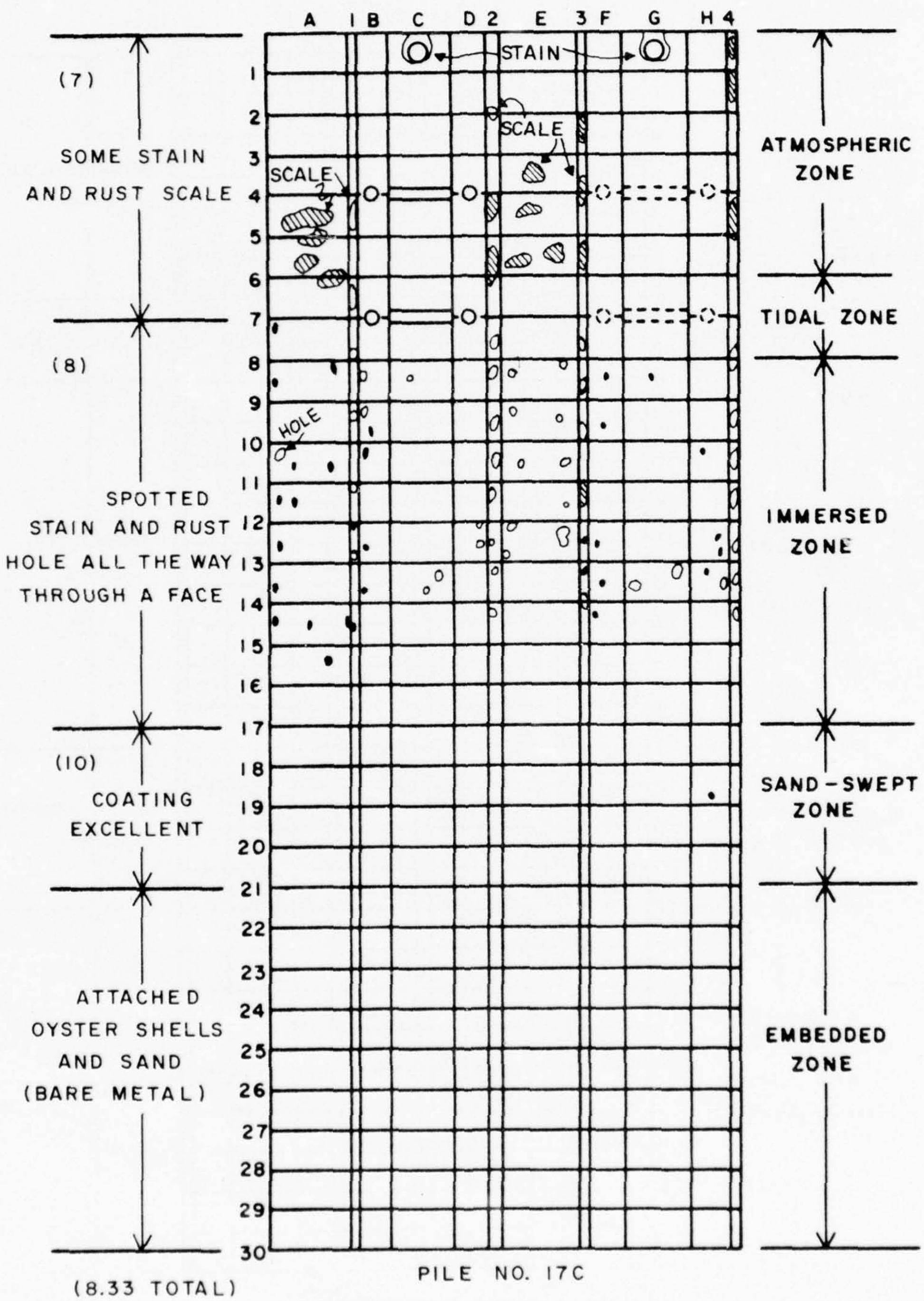
PILE NO. 15C
FLAME-SPRAYED ZINC WITH SARAN TOP COAT
ON CARBON STEEL



PILE NO. 16C

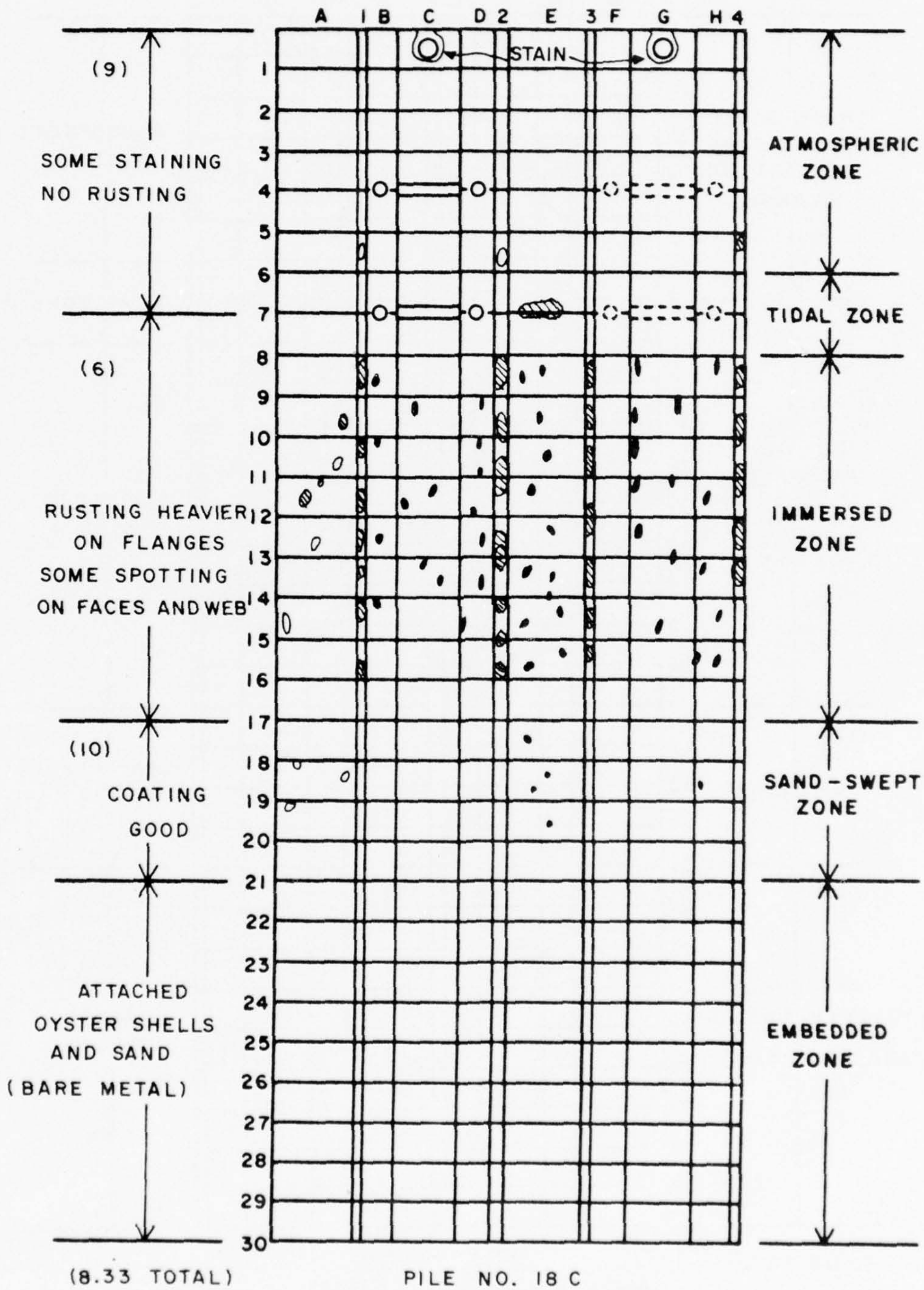
FLAME-SPRAYED ZINC WITH NAVY VINYL TOPCOAT

*TOPCOAT HAD PEELED BUT NO RUST WAS PRESENT



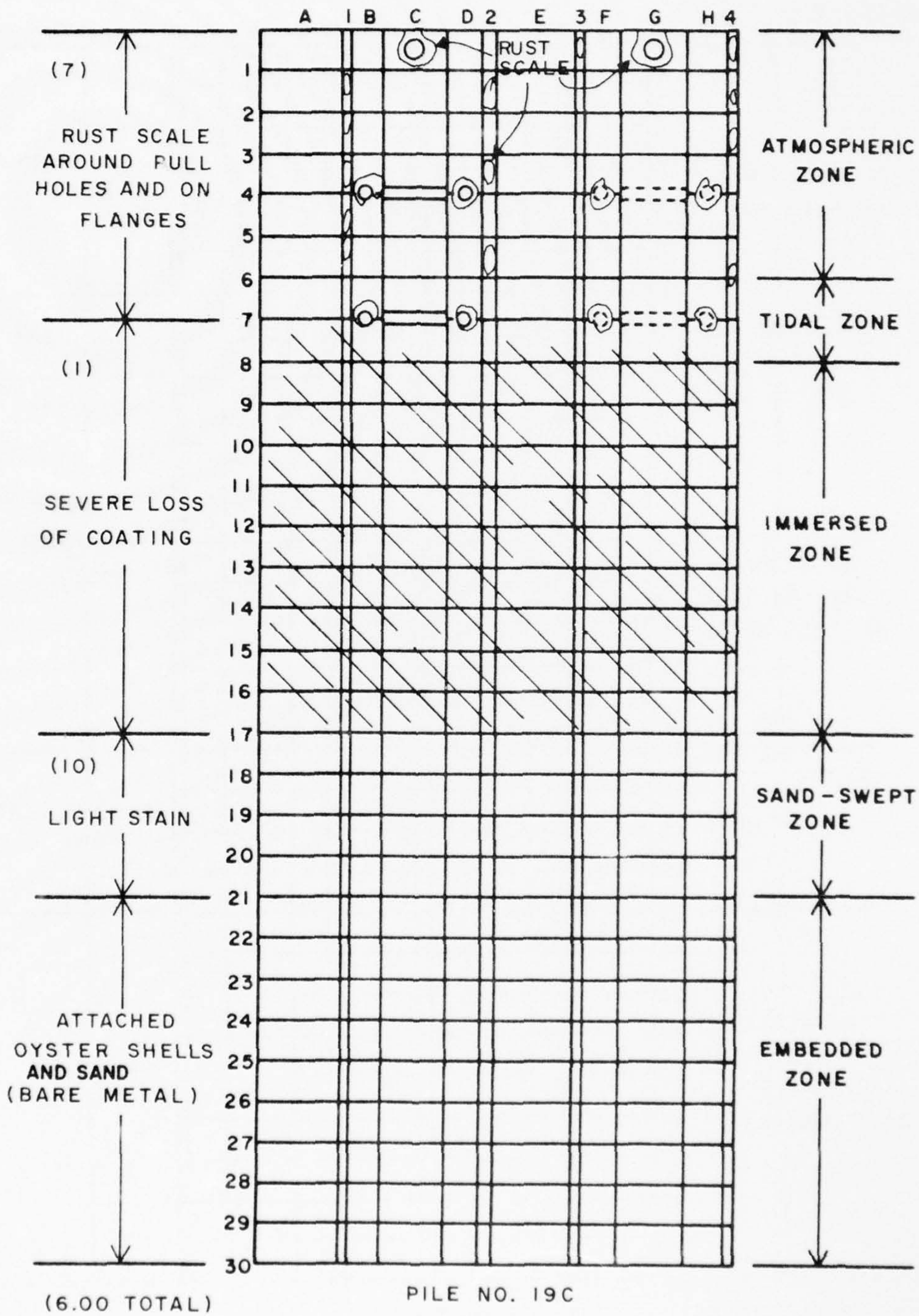
PILE NO. 17C

PHENOLIC MASTIC ON
CARBON STEEL



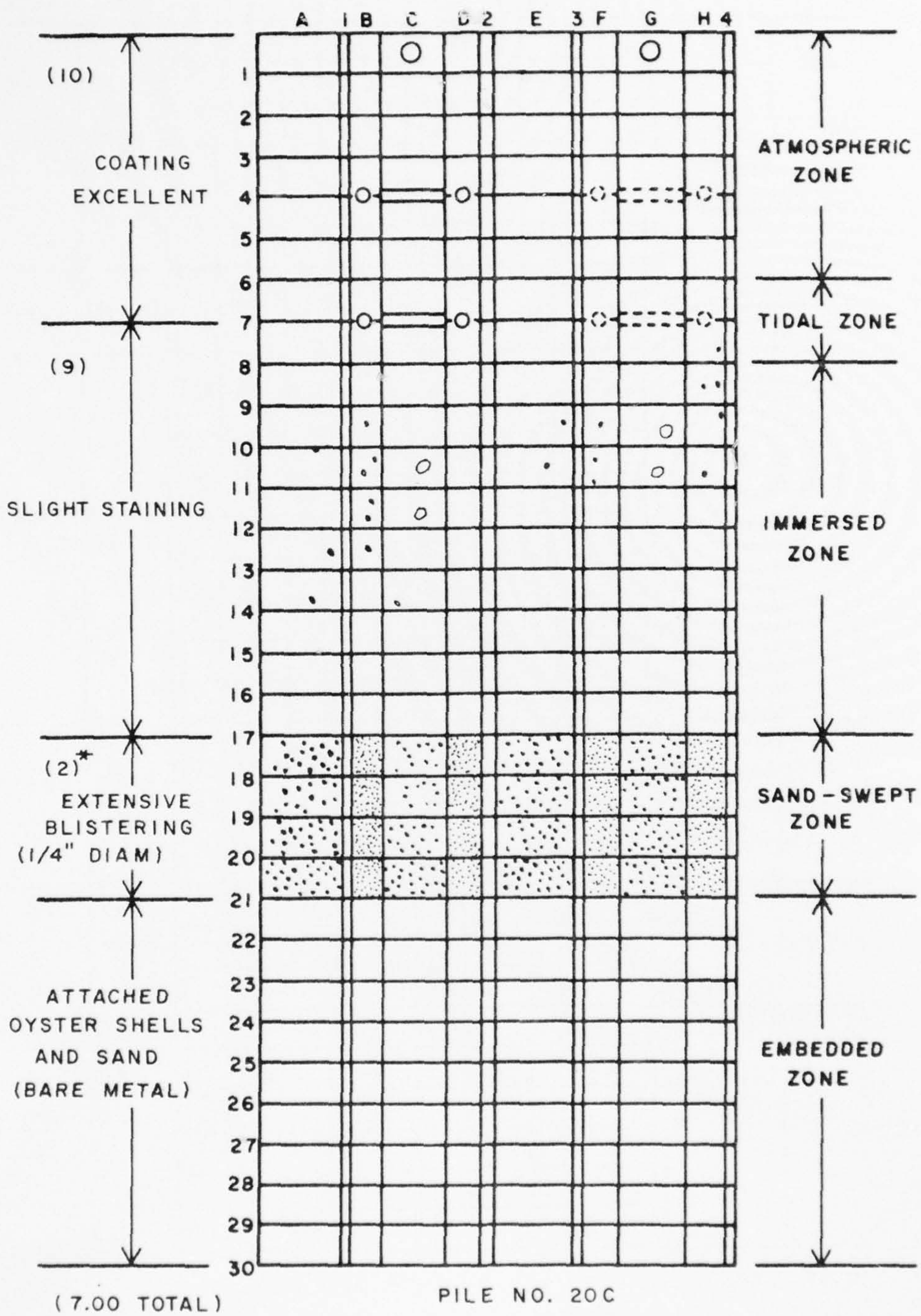
PILE NO. 18 C

COAL TAR EPOXY OVER INORGANIC ZINC-RICH PRIMER ON CARBON STEEL



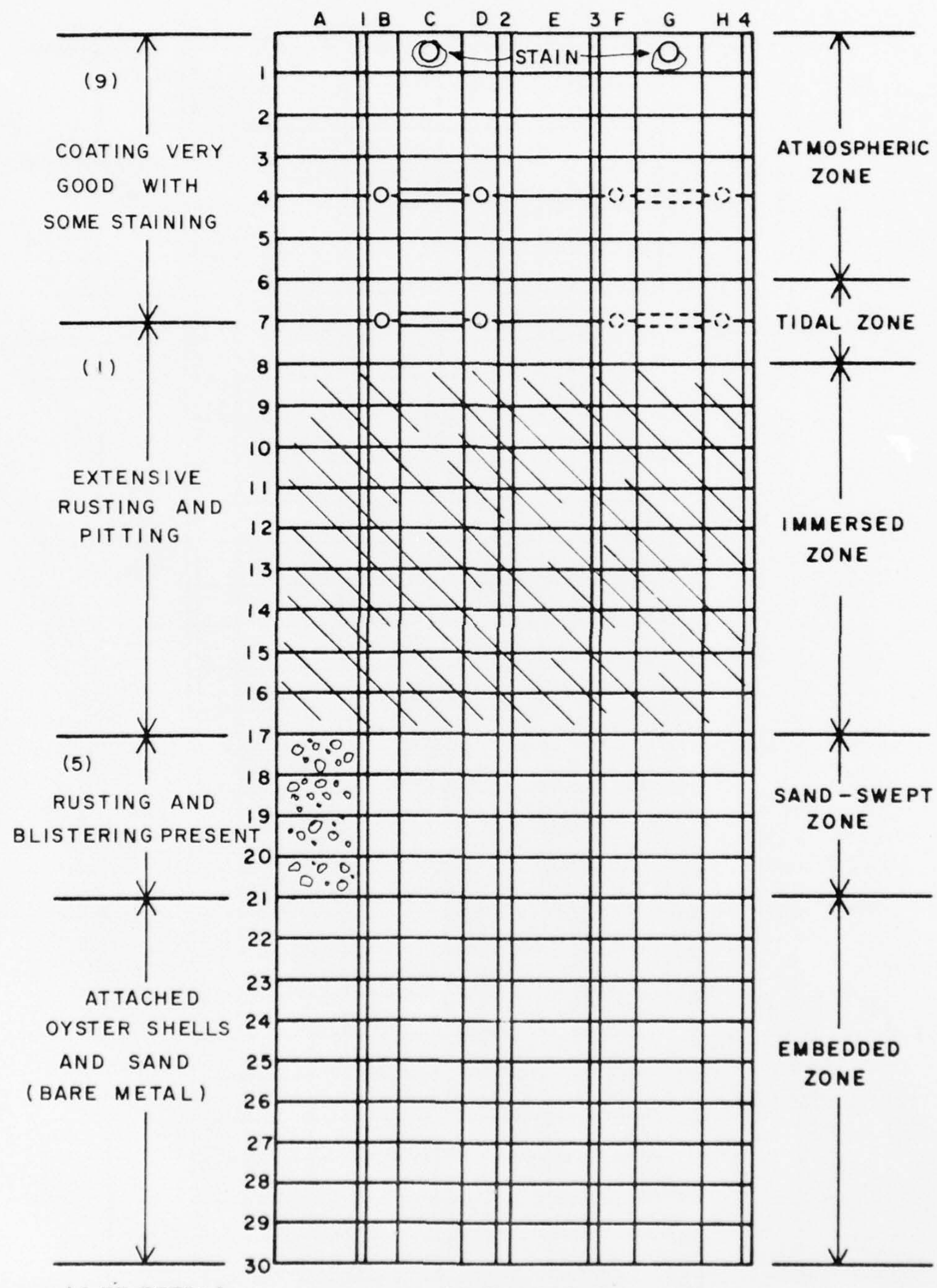
PILE NO. 19C

VINYL OVER INORGANIC ZINC-RICH PRIMER ON CARBON STEEL

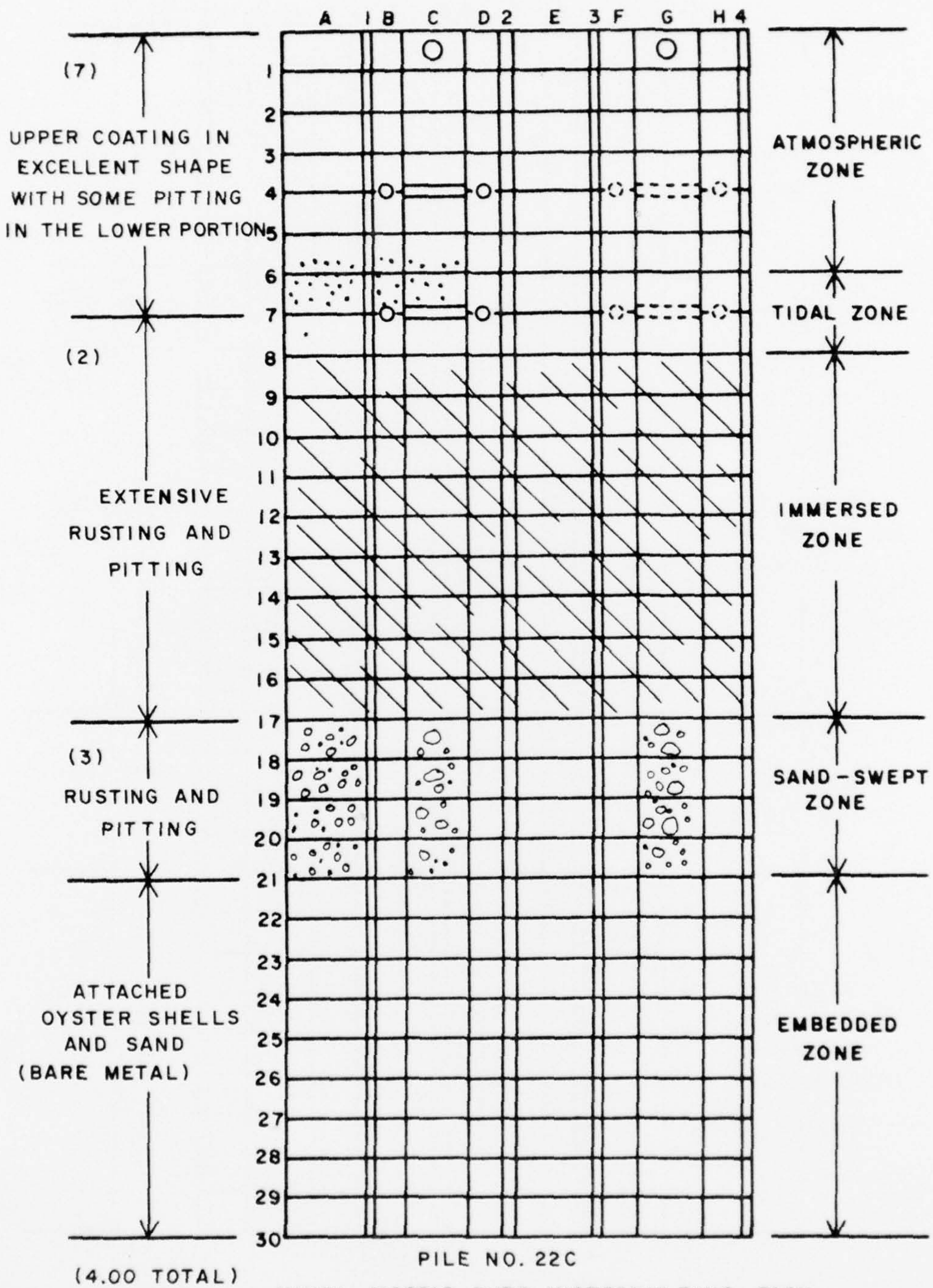


PILE NO. 20C

EPOXY-POLYAMIDE OVER INORGANIC ZINC-RICH PRIMER ON CARBON STEEL

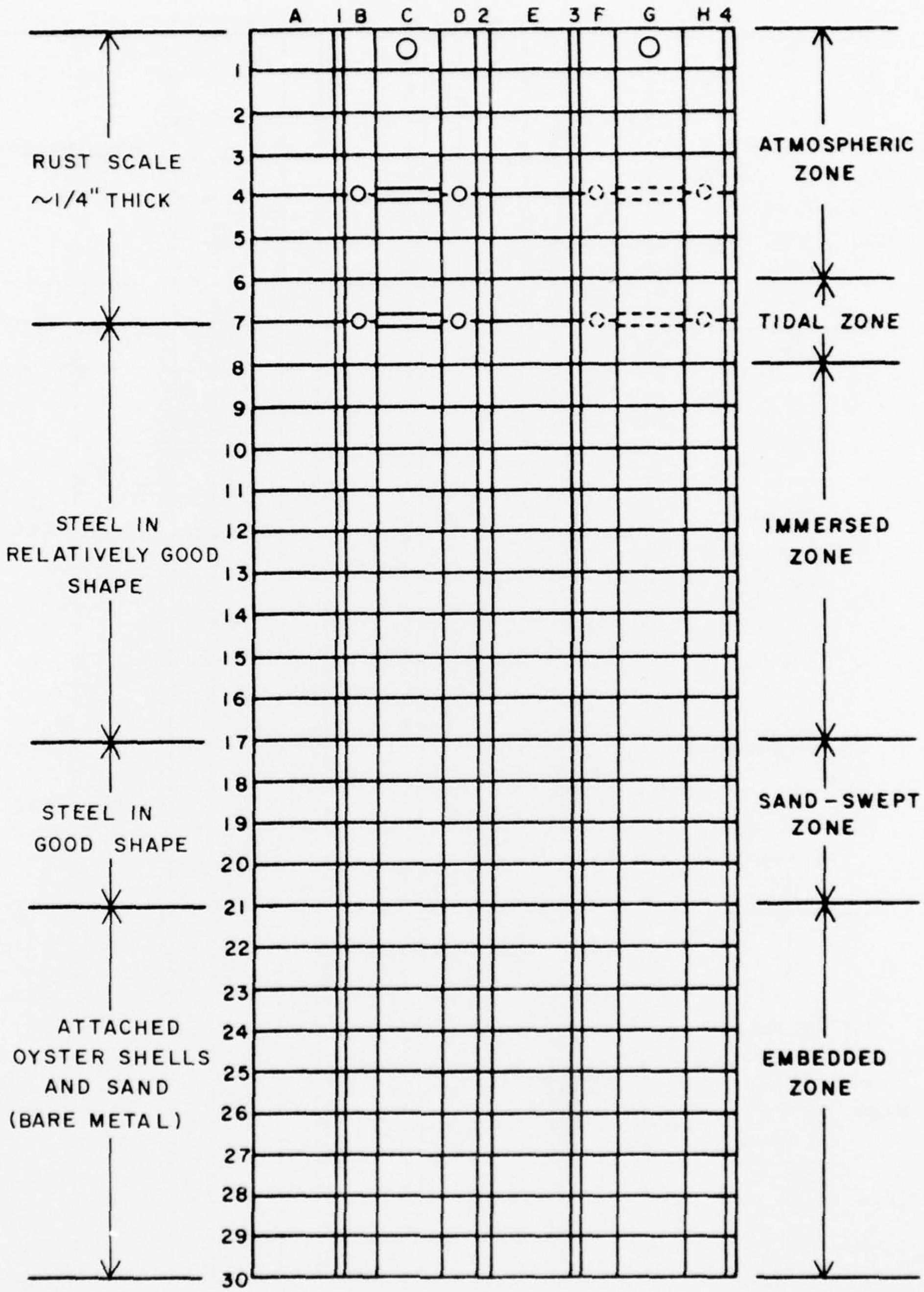


PILE NO. 21C
EPOXY-TAR OVER INORGANIC ZINC-RICH PRIMER ON CARBON STEEL



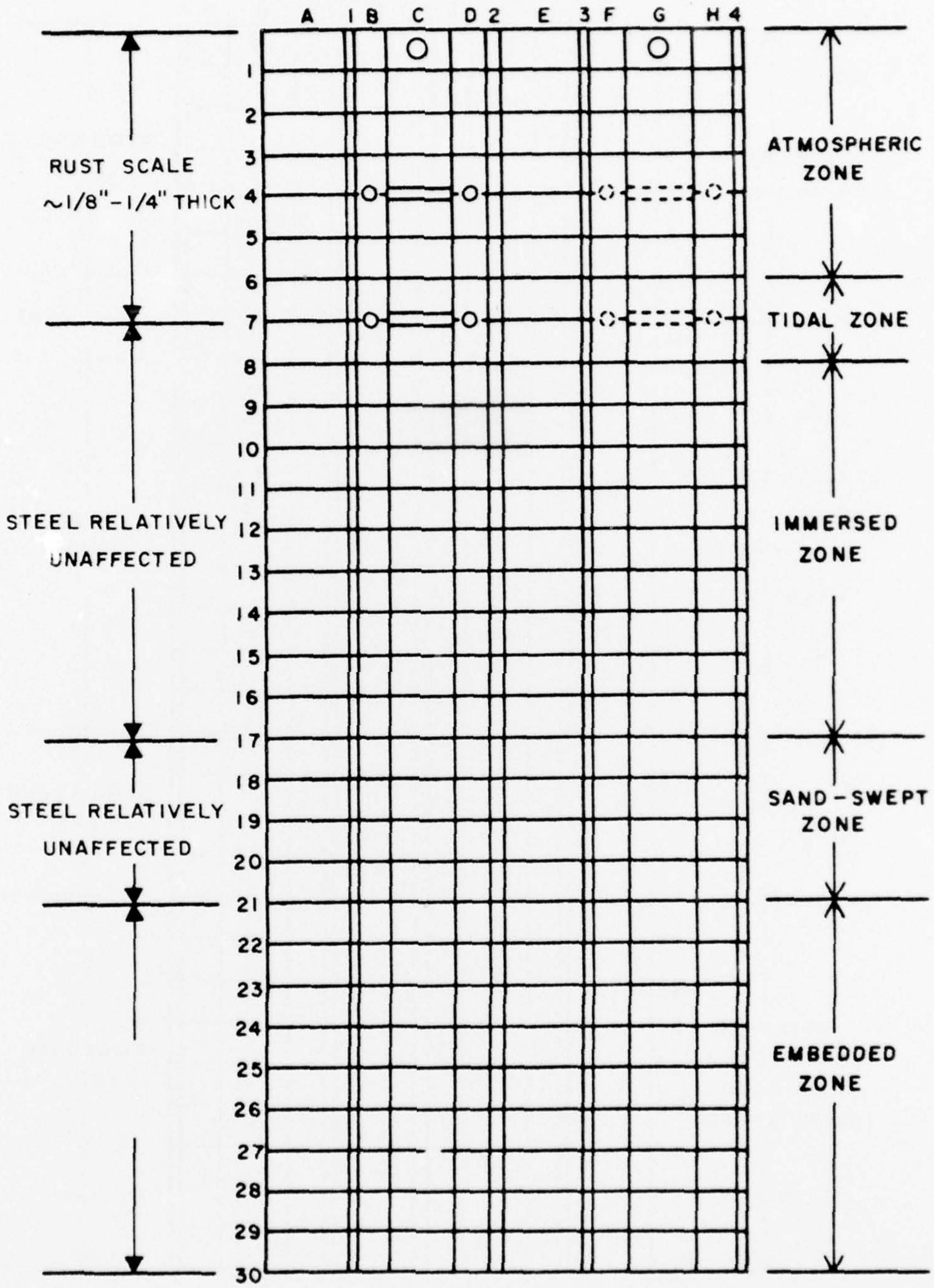
PILE NO. 22C

VINYL MASTIC OVER INORGANIC ZINC-RICH PRIMER ON CARBON STEEL

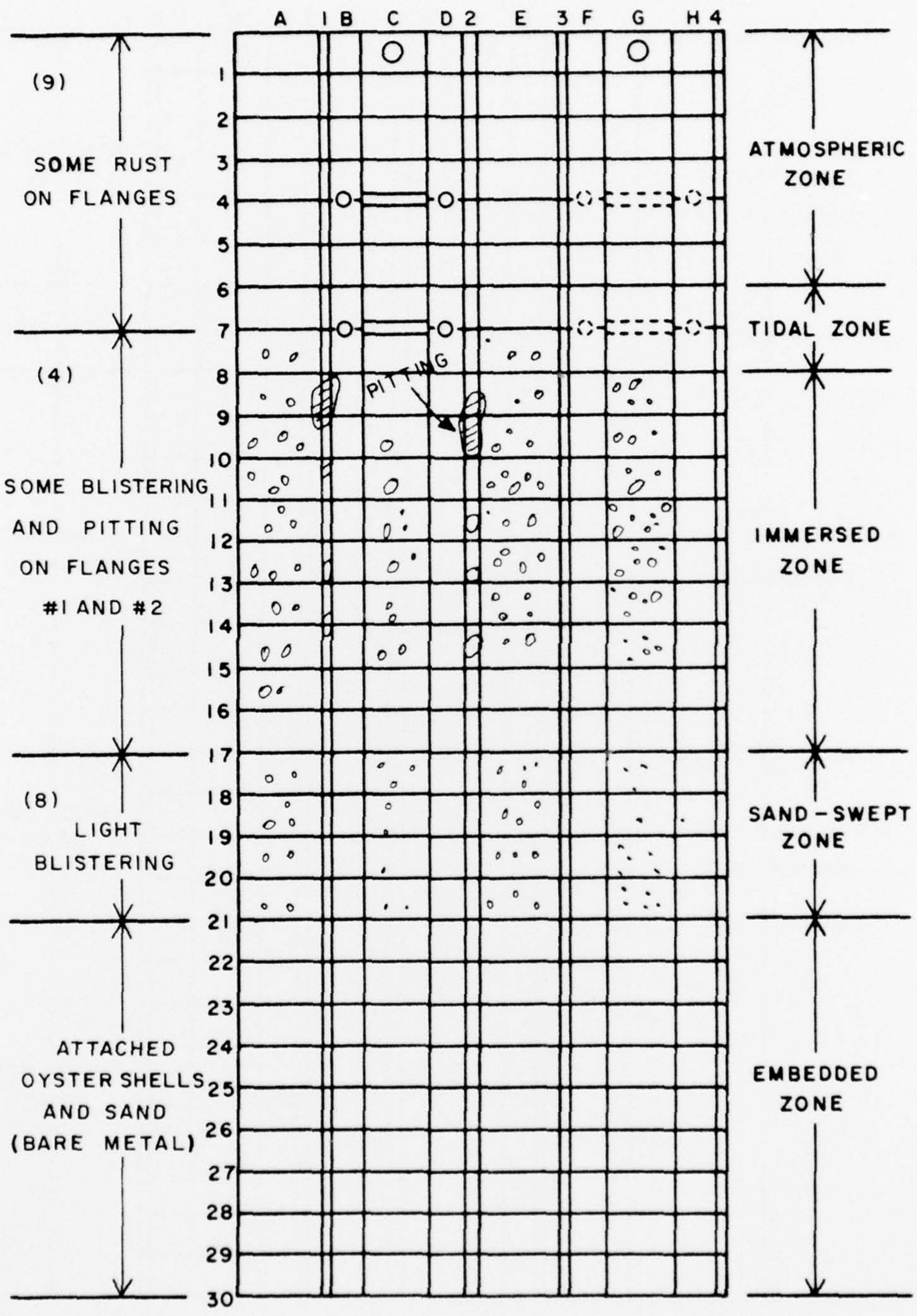


PILE NO. 23C

BARE MARINER STEEL

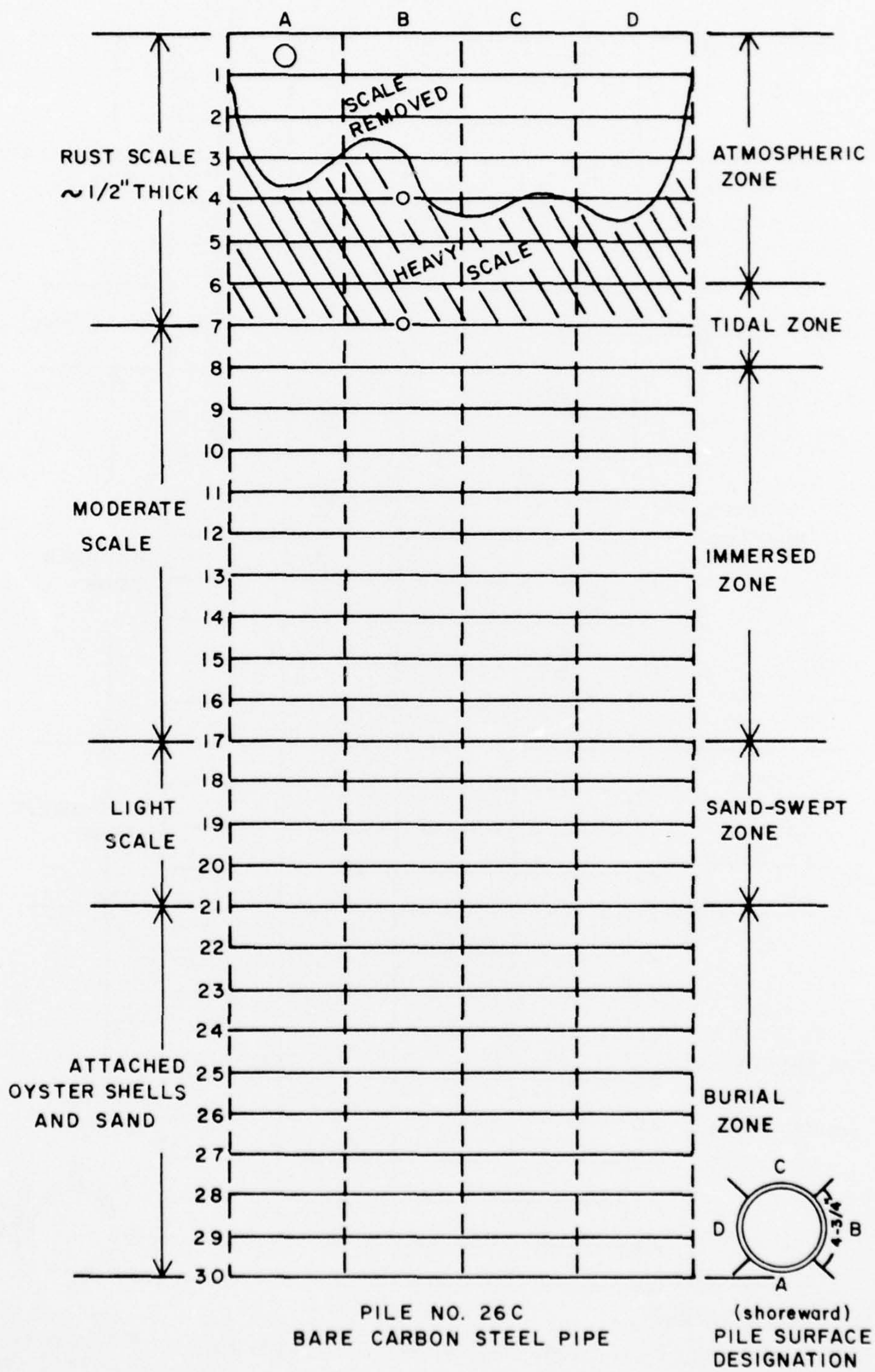


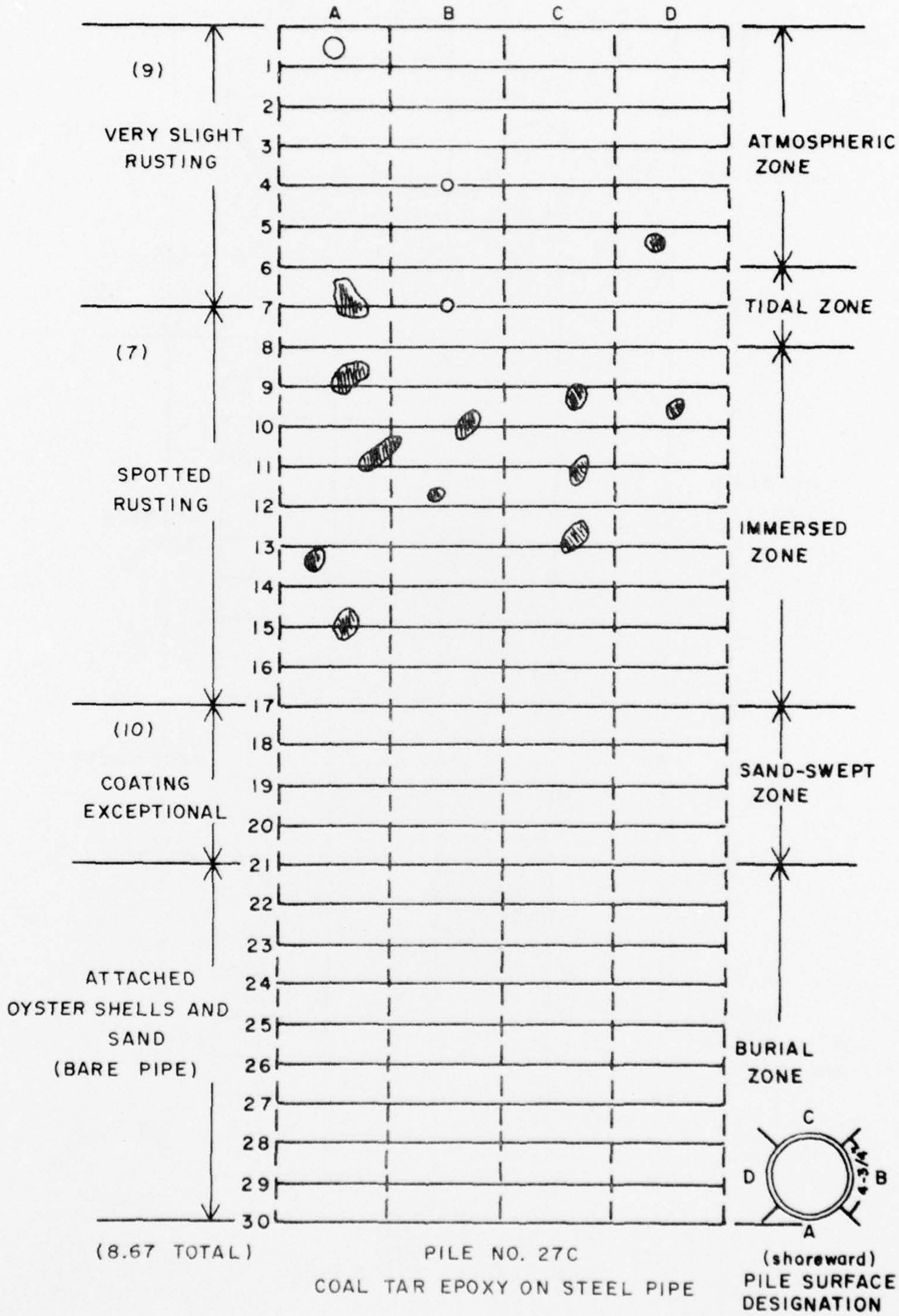
PILE NO. 24 C
BARE MARINER STEEL W/ZINC ANODES



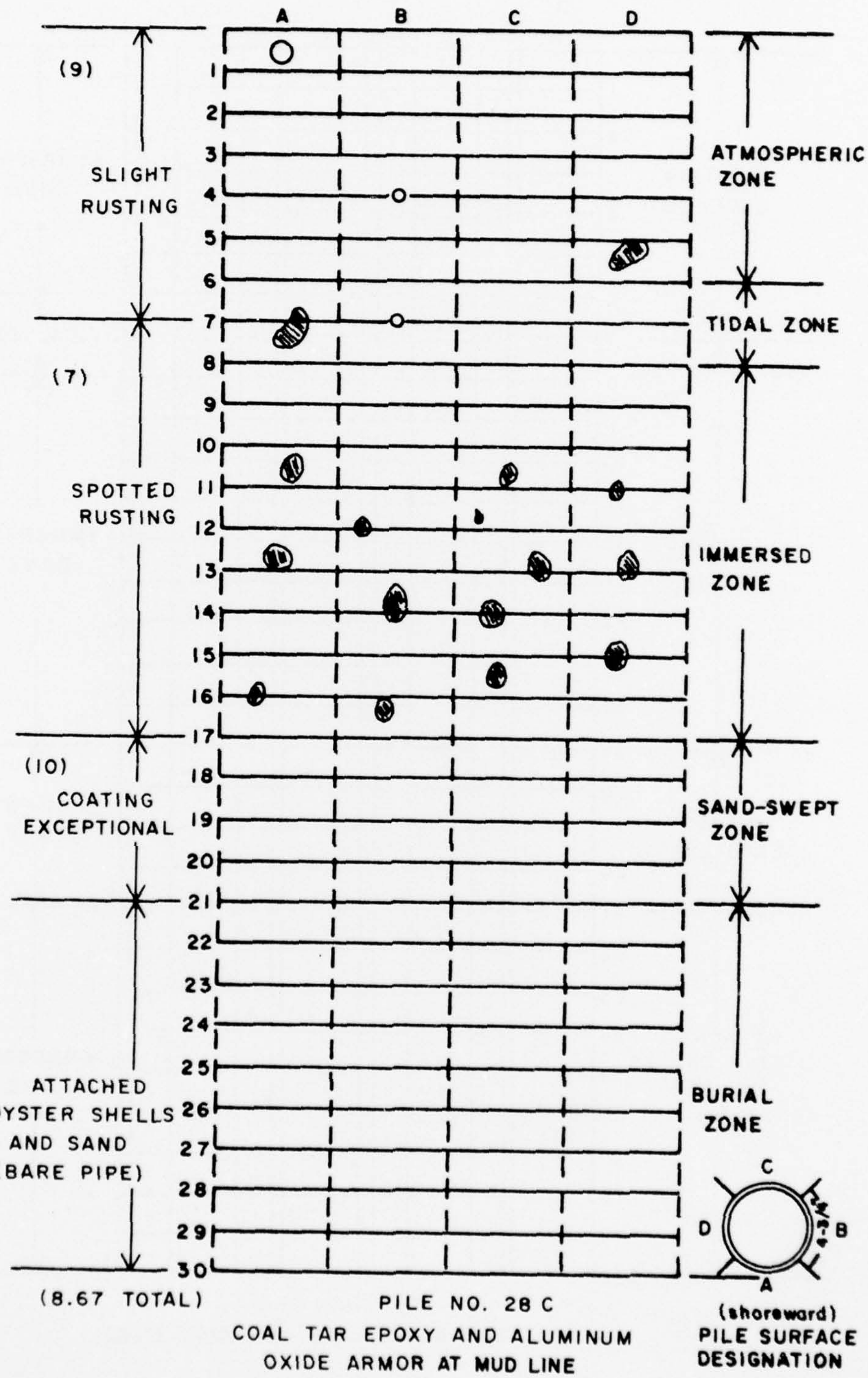
PILE NO. 25C

COAL TAR EPOXY ON BARE MARINER STEEL

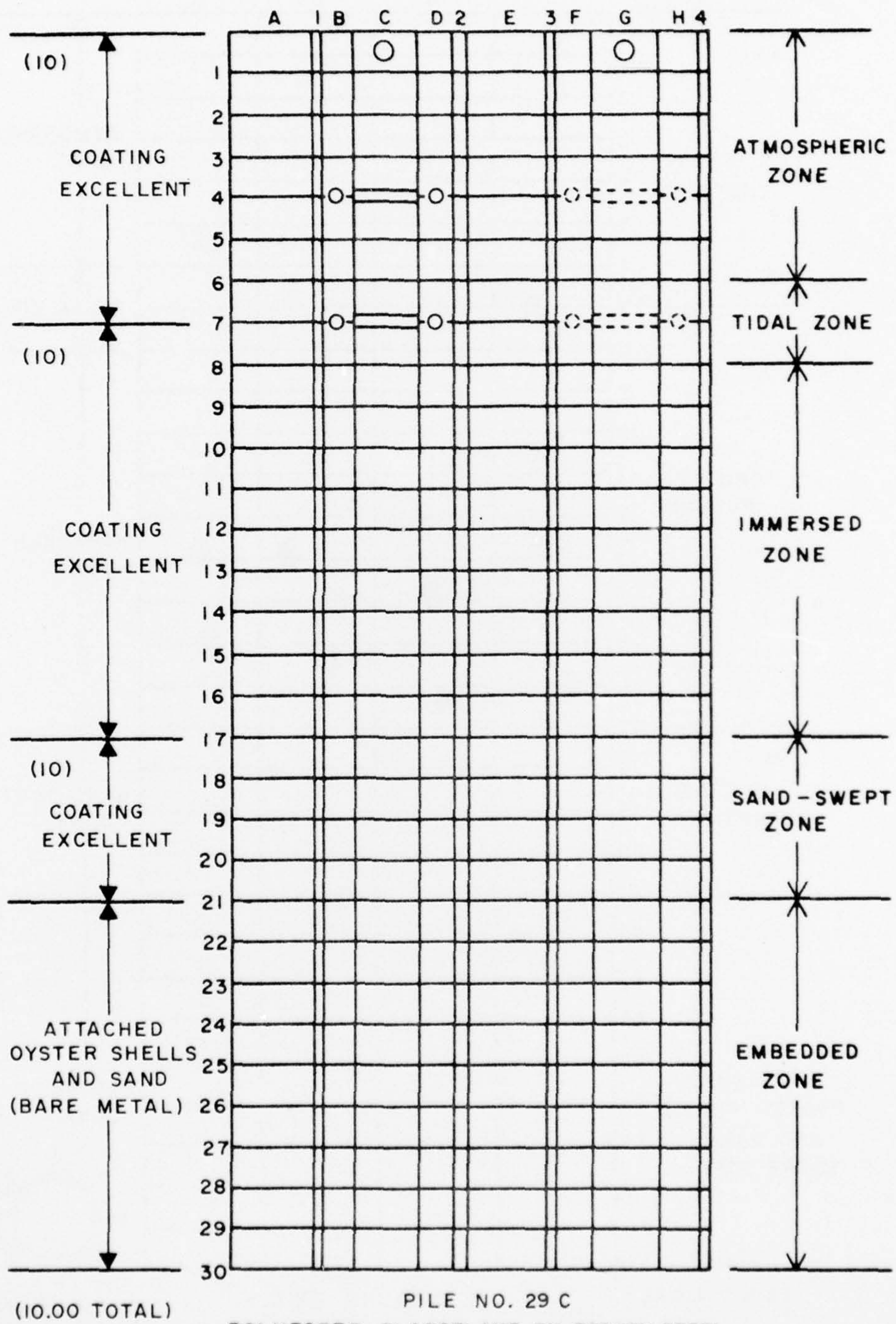

A
B
C
D
SCALE REMOVED
RUST SCALE
~1/2" THICK
HEAVY SCALE
ATMOSPHERIC ZONE
TIDAL ZONE
MODERATE SCALE
IMMERSED ZONE
LIGHT SCALE
SAND-SWEPT ZONE
ATTACHED OYSTER SHELLS AND SAND
BURIAL ZONE
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
C
D
B
A
4-3/4"
PILE NO. 26C
BARE CARBON STEEL PIPE
(shoreward)
PILE SURFACE DESIGNATION



PILE NO. 27C
COAL TAR EPOXY ON STEEL PIPE



PILE NO. 28 C
COAL TAR EPOXY AND ALUMINUM OXIDE ARMOR AT MUD LINE



PILE NO. 29 C
POLYESTER GLASSFLAKE ON CARBON STEEL

APPENDIX C:

DERIVATION OF PILE STRUCTURE FACTOR

The design application for the piles tested is unknown. However, if one considers the top of the pile as the point of attachment in the design application, then the top of the pile may be subject to four sets of forces and/or couples in general. The forces and couples on the pile top are termed:

1. Axial force P running lengthwise along the pile
2. Transverse forces, F_x and F_y, in principal moment of inertia axis directions
3. A couple, T, producing a torsional moment on the pile.

These forces and couples will be transmitted into the pile and result in stresses that must be designed for in any application.

Computation of the stresses within the pile requires use of all the structural section factors considered of importance to this study. It should be noted that the mode of failure of the pile may be other than that related to the pile stress, e.g., axial buckling or torsional buckling. However, the structural section factors needed in these expressions are also contained in all the expressions for stress within the pile resulting from end loading. Examination of the expressions for pile stress is a convenient means of defining the structural section factors. It should also be noted that only factors entering the elastic design of the piles are considered. This simplifies the presentation and provides adequate information considering the coarseness of the analysis based on the minimal adequacy of the data obtained for structural evaluation.

For an axial load P on a pile, there are two expressions for stress that are important in the pile design application. The first expression is the compressional (or tensile) stress on the section defined by

$$\sigma = \frac{P}{S_A} \qquad \text{[Eq C1]}$$

where σ = compression/tension stress
P = axial load
S_A = cross-sectional area of the pile.

The second expression is the shear stress acting on the surface of the pile from the metal-sediment interface. This is defined by

$$\tau = \frac{P}{C_A} \qquad \text{[Eq C2]}$$

where τ = pile surface shear stress
P = axial load
C_A = circumferential area.

In the pile design for axial load (neglecting buckling for the time being), S_A and C_A are structural section factors of importance. A decrease in either S_A or C_A will affect the design stress.

For the transverse loads on a pile acting along the principal axes of inertia, F_x and F_y, a bending moment is created in the pile. The expression for the stress in the pile resulting from application of F_x and F_y is

$$\sigma = \frac{M_x'}{I_x'} y + \frac{M_y'}{I_y'} x \qquad \text{[Eq C3]}$$

for

$$M_x' = M_x - M_y (I_{xy}/I_y)$$

$$M_y' = M_y - M_x (I_{xy}/I_x)$$

$$I_x' = I_x - I_{xy}(I_{xy}/I_y)$$

$$I_y' = I_y - I_{xy}(I_{xy}/I_x)$$

where σ = bending stress
x = distance of point of application from the x-axis (x-axis a centroidal axis)
y = distance of point of application from the y-axis (y-axis a centroidal axis)
M_x = bending moment about the x-axis from components F_x and F_y
M_y = bending moment about the y-axis from components of F_x and F_y
I_x = moment of inertia of the section about the x centroidal axis
I_{xy} = product of inertia about the x, y centroidal axes
′ denotes corroded section.

This formula is for unsymmetrical bending and is of sufficient generality to define the stress on a section of the pile at point x, y. The structural section factors of importance here are I_x, I_y, and I_{xy}. These factors are also important in lateral buckling of piles.

The last factor of importance in the study is derived from the expression for shear stress on the pile resulting from a couple, T, on the pile. The shear stress may be written

$$\tau = \frac{T\,r}{J} \qquad \text{[Eq C4]}$$

where τ = shear stress from torsion
T = couple on section
r = section dimension
J = polar moment of inertia of the section.

For rectangular sections or sections composed of rectangles, J is taken as

$$J = \sum_k (1/3)bh^3 \qquad \text{[Eq C5]}$$

where b = long dimension of the rectangle
h = short dimension of the rectangle
k = index over all rectangles composing the section.

J is also found in design expressions for torsional stability of structural members. The centroid of the section is computed from

$$\bar{x} = \frac{\Sigma \bar{x}_i A_i}{\Sigma A_i} \qquad \text{[Eq C6]}$$

where $\bar{x}$ = total section centroid
$\bar{x}_i$ = centroid for i^{th} rectangle
A_i = area of i^{th} rectangle.

The moments of inertia about the principal axes are determined from the formulas

$$I_{xx} = \frac{I_x + I_y}{2} + \frac{I_x - I_y}{2}\cos 2\theta - I_{xy}\sin 2\theta \qquad \text{[Eq C7]}$$

$$I_{yy} = \frac{I_x + I_y}{2} + \frac{I_x - I_y}{2} c\theta 2(2\theta + \P) - I_{xy}\sin(2\theta + \P) \qquad \text{[Eq C8]}$$

for

$$\tan 2\theta = \frac{2I_{xy}}{I_y - I_x}$$

where I_x, I_y, and I_{xy} are as defined above.

Because of differences in measured pile cross sections in the embedded (buried) zone, defining each pile's nominal section separately was necessary. This was done by averaging the flange and web thicknesses for the buried section (bottom 9 ft [2.7 m]), which was assumed to corrode at a constant rate of 1.1 mil/yr (0.03 mm/yr). The corroded section dimensions were obtained similarly by averaging the flange and web thicknesses over the corroded section.

A computer program was developed to provide a convenient means of comparing the pile section configurations. The program takes the four flange and web thickness measurements for each section along a given pile, in addition to a nominal section flange and web thickness, and computes the following quantities:

1. The pile nominal section based on an average of flange and web thickness measured from the portion of the pile in the sediment

2. $\bar{x}$, $\bar{y}$, I_x, I_y, I_{xy}, S_A, C_A, J, I_{xx}, I_{yy} for the nominal pile section and the corroded pile section with or without a hole for each section along the pile length for which measurements were taken

3. The ratio of each of the quantities in 2 of the corroded section to the nominal section and a pile structural factor

4. The mean and standard deviation of all the section properties plus -3σ to $+3\sigma$ variation of the section properties

5. A gross average flange thickness and web thickness over all measurements made and the ratio of the section properties based on this average to the nominal section properties, the mean and standard deviation of measurements of the gross section, the -3σ to $+3\sigma$ variation, and a pile structural factor.

Table C1 presents the weighting factors for each of the structural factors. The factors were determined based on the influence of each structural factor on the integrity of the pile.

The pile structural section factor is defined to be a weighted sum of the corroded section properties over a weighted sum of the nominal section properties, that is

$$\text{PSSF} = \frac{w_1\bar{x}' + w_2\bar{y}' + w_3 I_x' + w_4 I_y' - w_5 |I_{xy}'| + w_6 S_A' + w_7 C_A' + w_8 I_{xx}' + w_9 I_{yy}' + w_{10} J'}{w_1\bar{x} + w_2\bar{y} + w_3 I_x + w_4 I_y - w_5 |I_{xy}| + w_6 S_A + w_7 C_A + w_8 I_{xx} + w_9 I_{yy} + w_{10} J} \qquad \text{[Eq C9]}$$

Table C1

Structural Properties and Associated Weighting Factors

Property	Definition	Weighting Factor
$\bar{X}$	Centroid of section x	0
$\bar{Y}$	Centroid of section y	0
I_x	Moment of inertia about x	0.05
I_y	Moment of inertia about y	0.05
I_{xy}	Product of inertia about x, y	−0.05
S_A	Cross-sectional area of pile	0.20
C_A	Circumferential area of pile	0.05
J	Polar moment of inertia of section	0.20
I_{xx}	Product of inertia for x	0.20
I_{yy}	Product of inertia for y	0.20

where

PSSF = pile structural section factor

W_i = i = 1, 10 weighting factor

' denotes corroded section

and other variables are as defined above for the corroded and nominal sections.

The pile structural section factor is inadequate to fully assess the pile structural degradation because it does not consider the surface condition of the piles. The measurements made on either the flanges or web seldom reflect the depth of the corrosive pits or whether either flange or web contains holes. The size and density of pits or irregular surface on any one particular section can be important factors in assessing the degree of structural degradation.

As a result of these observations, a second factor that qualitatively assesses the effect of surface structure on the overall section properties was developed. This second factor, termed the structural surface factor (SSF), is defined as follows:

$$SSF = 1 - k_1 \left(\frac{10-x}{10}\right)^{k_2} \qquad \text{[Eq C10]}$$

where SSF = structural surface factor

k_1 = magnification factor

k_2 = importancy factor

x = surface factor (an integer number from 0 to 10).

For a pile with no surface degredation (x = 10), SSF is 1.0. For a pile with severe pitting and structural degredation (x = 1), SSF is between 0 and 1.0, depending on the values of k_1 and k_2. The particular selection of the expression for the SSF with k_1 and k_2 variable provides a degree of flexibility that allows modeling according to the degree of importance attached to the SSF.

The pile structural factor (PSF) is the product of the pile structural section factor and the structural surface factor:

$$PSF = (PSSF) \times (SSF) \qquad \text{[Eq C11]}$$

Table C2 shows the PSFs for each pile for three combinations of k_1 and k_2.

Table C2

Pile Structure Factors

Pile No.	PSF*	Rank*	PSF**	Rank**	PSF†	Rank†	Normalized Structure Factor††
1C	.77337	26	.78139	26	.79497	26	77.05
2C	.86509	23	.88146	23	.90397	23	86.92
3C	.82063	24	.83287	24	.85168	25	82.13
4C	.94852	15	.97338	15	.99446	14	95.99
5C	.99845	5	.99845	5	.99845	11	98.48
6C	.92651	18	.94716	18	.97208	17	93.40
7C	.97027	9	.99193	8	1.00095	6	97.82
8C	.91861	20	.93231	20	.95336	20	91.94
9C	.99740	6	.99740	6	.99740	12	98.35
10C	1.00355	3	1.00355	3	1.00355	4	98.96
11C	.90790	21	.93139	21	.94660	21	91.84
12C	.88991	22	.91199	22	.93479	22	89.93
13C	.99612	7	.99612	7	.99612	13	98.23
14C	.99961	4	.99961	4	.99961	8	98.57
15C	.96162	14	.98650	13	1.00261	5	97.28
16C	.96935	10	.99100	9	1.00001	7	97.72
17C	.96821	12	.98983	11	.99883	10	97.61
18C	1.00646	2	1.00646	2	1.00646	2	99.25
19C	.93824	17	.95919	17	.96791	18	94.58
20C	.96384	13	.98878	12	1.00492	3	97.50
21C	.92116	19	.93860	19	.96256	19	92.56
22C	.94298	16	.96769	16	.98864	15	95.42
23C	.81520	25	.83063	25	.85183	24	81.91
24C	.97616	8	.97616	14	.97616	16	96.26
25C	.96890	11	.99054	10	.99954	9	97.68
29C	1.01409	1	1.01409	1	1.01409	1	100.00

*Refers to $k_1 = 0.1$ and $k_2 = 0.5$

**Refers to $k_1 = 0.1$ and $k_2 = 1.0$

†Refers to $k_1 = 0.1$ and $k_2 = 2.0$

††Refers to calculations made from PSF for $k_1 = 0.1$ and $k_2 = 1.0$.

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